

**EXPLORATION OF HIGH DYNAMIC RANGE PHOTOGRAPHY AS A  
USEFUL TOOL FOR LIGHTING DESIGN**

**BY**

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and the Graduate Faculty of the University of Kansas in partial fulfillment of the  
requirements for the degree of Master of Science.



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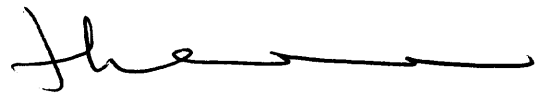
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EXPLORATION OF HIGH DYNAMIC RANGE PHOTOGRAPHY AS A USEFUL  
TOOL FOR LIGHTING DESIGN

A handwritten signature in black ink, appearing to read 'Hongyi Cai', is positioned above a horizontal line.

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## **ABSTRACT**

This thesis introduces a camera-aided imaging method, better known as high dynamic range (HDR) photography, and how this method could potentially help improve the quality of lighting design analysis. The imaging method captures 18 million luminance values across an interior or exterior luminous environment and stores the data on an HDR image. The HDR image is then calibrated and uploaded in a MatLab code to plot two-dimensional luminance and illuminance gradient maps for further evaluation of the luminous environment. Four case studies were conducted to validate the application of the imaging method in the lighting design field. The case studies include electrically lit interior spaces, day lit and electrically lit interior spaces, and exterior lighting spaces. The first case study was conducted in a classroom in Regnier Hall at the University of Kansas. The classroom had fluorescent fixtures and no daylight. The measurement was taken on June 14<sup>th</sup> at 11AM local time. The second case study was conducted in a classroom in the Business Engineering Science and Technology Building at the University of Kansas. The classroom had linear LED down lights mounted in the ceiling and windows on the north and south sides for daylighting. The measurement was taken on June 14<sup>th</sup> at 10:30 AM local time. The third case study looked at the lobby of the Business Engineering Science and Technology Building, which has floor-to-ceiling windows on the north and south side for daylighting, and electric down lights. The third study was conducted on June 14<sup>th</sup> at 10 AM local time. The fourth case study looked at the exterior of the Blue Valley High School in Overland Park, KS, on October 18<sup>th</sup> at 8 PM local time. The camera was aimed at the south façade of the building for measurement of the luminous environment. Luminance values extracted from the HDR images obtained in each case study were used

to evaluate the lighting quality of the luminous environments and improve problematic lighting conditions, if any. An online questionnaire survey with the yes-or-no questions regarding several different HDR images was then conducted to find out whether lighting designers and professionals would be interested in this camera-aided imaging method. It was found that most designers thought the new technology would be useful but time consuming and not very easy to understand. However, they all agreed that it could potentially be a very good tool to use to improve the lighting design practice. The camera-aided imaging method was tested in those four case studies and thus recommended as a useful tool in the lighting design profession for students and entry-level engineers, architects, and lighting designers.

#### **KEYWORDS**

Camera-Aided Imaging Method, Evalglare, Luminance, Gradient, Lighting Quality, Lighting Concepts, Lighting Analysis, Measurements, Human Factors, Visual Perception.



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## **CHAPTER 1: INTRODUCTION**

### **1.1 Background**

Lighting designers and engineers often create a design in a space according to typical lighting standards. A large portion of work in daylighting design resides in improving the lighting in an existing space or creating new projects. The lighting can be analyzed with conventional tools like light meters and computer programs such as AGI, Radiance, DaySim, Revit, and SketchUp. Lighting design practice is very subjective and can often be an inconsistent but creative practice as a result of the different visions from lighting designers. It may be difficult to receive quantitative data to analyze the creative aspects of lighting design.

Within most architectural spaces, lighting design is done with the guidance of three core aspects. The first is that light measurement techniques are used for acquisition of spatial light distribution using qualitative and quantitative measures. The second is the light data in specific scenes that can be quantitatively measured for their lighting efficiency, color rendering index, as well as potential discomfort or disability glare. Third, the human factors are also considered within a luminous environment.

This thesis introduces a camera-aided imaging method to be used by lighting practitioners to evaluate the quality of interior and exterior luminous environments. Standard lighting measurements use point-by-point methods which do not account for all of the daylight illumination levels and do not provide information about the environment that the human eyes can see. High Dynamic Range (HDR) photography measures both

luminance and geometry of target points at a pixel level across the entire lighting scene using a single digital camera.

Currently, there is no quantitative or graphical method to analyze the creative aspects of lighting design, one that bridges the gap between subjective and empirical objective design. The use of AGI and Revit may provide beneficial renderings but it only results in an image of how the luminous environment might be when it is constructed and one might not fully understand the luminous lit space from a simple computer rendering. HDR imaging offers the lighting designer a tool to bridge this gap. However, the problem resides in how to process and interpret these images.

## **1.2 Current Status of the Lighting Design Practice**

Designers in the lighting field often create unique architectural spaces that are aesthetically pleasing and considerate of the users comfort. However, what makes these spaces beautiful and comfortable? Studies show lighting designers why a specific space is beneficial for human use through the analysis of technologies. These studies show how to design with the effects of light, rather than the light itself. Designing with light is both an art and a science.

When designers create illumination in a space they usually abide by the Illuminating Engineering Society (IES) and International Association of Lighting Designers (IALD) standards. Depending on what kind of space is being designed, different lighting solutions are considered. For a space like an office, for example, the lighting design needs to be considered by using as much natural light as possible, choosing light fixtures that are energy efficient, and overall, trying to avoid disability



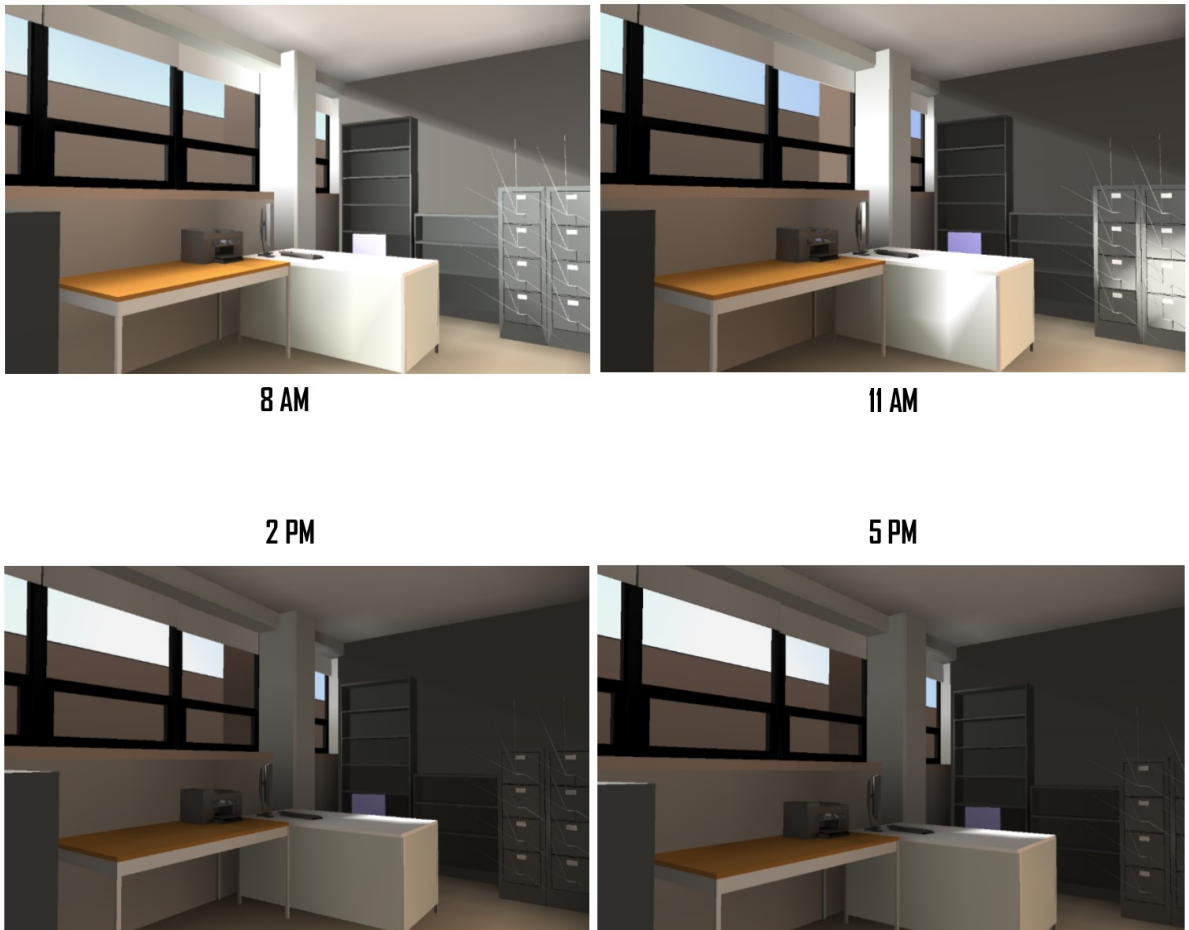
glare for the users and enhance productivity. For a space like a museum, the lighting design needs to be considered by using specific light fixtures that will not harm the artwork, provide high color rendering, and highlight the architectural spaces. For a space like a movie theatre, the lighting design needs to be considered by using a lower amount of illuminance as to not cause disturbance to the users watching a movie in the space.

As one can see, each space is unique and needs to be designed differently based on the needs of the users in the space. A designer may also consider the amount of light based on foot candles and lux inside a space abiding by the typical IES standards.

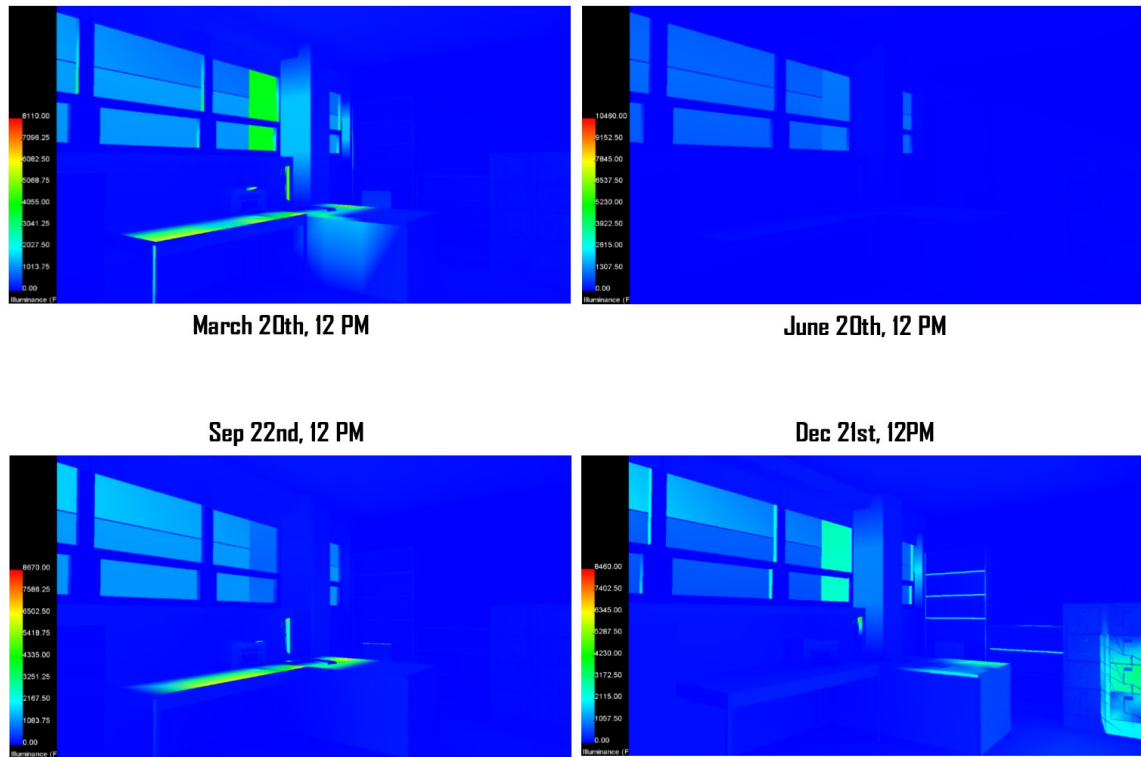
When a designer conducts design work, the light fixtures are chosen and placed in strategic locations within the space. The cut sheets of the lighting fixtures are usually looked at and considered and then placed into a rendering program such as AGI or Revit. A sample of a computer rendering done on AGI is shown in Figure 1.2.1 and Figure 1.2.2. These basic renderings show the designer how the light output might potentially look and how much light it might provide.

These tools might be useful for new projects; however, the renderings are often generated based on how much light falls on different surfaces, not based on how bright the surfaces might be, which is consistent with the human vision. In addition, renderings work for projects still under design, but do not necessarily work for existing renovation projects when renderings may not represent their actual luminous environments. It may be difficult to model an existing space with all of the necessary details and analyze its luminous environment so that one may re-design it in a more efficient manner. All of these factors might be tedious and labor intensive. Because of its high efficiency and quick turnaround, High Dynamic Range photogrammetry could supplement light and

geometry measurement in many lighting applications, making it a useful tool for lighting designers to use while analyzing an existing space. These images were made using AGI renderings for a typical office space at the University of Kansas. The renderings considered the different times of day for daylight entrance into the office.



**Figure 1.2.1:** Lighting Studies Using Computer Aided Programs <sup>1</sup>



**Figure 1.2.2:** False Color Images <sup>1</sup>

### 1.3 High Dynamic Range Photography

High dynamic range photography takes images of an existing space and uses a set of images to capture a greater dynamic range photogrammetry for synchronous acquisition of luminance points across a scene and their 3D coordinates XYZ in the field. Standard lighting measurements use point-by-point methods which do not account for all of the daylight illumination levels and do not provide information about the environment that the human eyes can see. HDR photography measures the luminance of target points at a pixel level across the entire lighting scene using a single digital camera.

HDR photography takes multiple photographs with different exposures and measures luminance of target points at pixel levels across an entire scene within 1-2

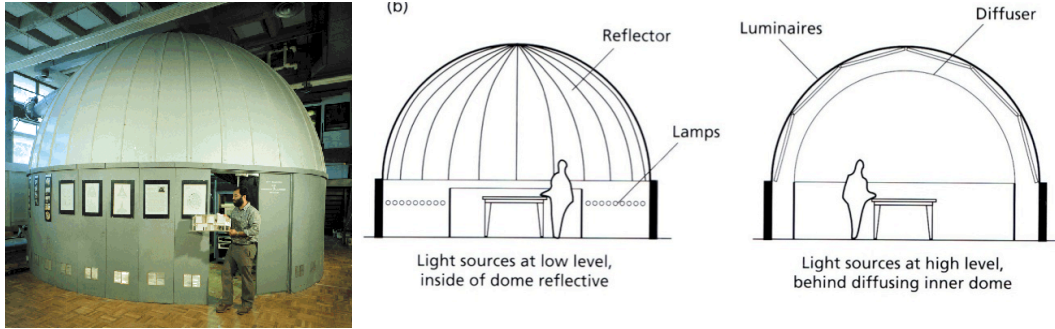
minutes. The camera response function is derived through a self-calibration process from the multiple exposed photographs, which is then used to fuse the photographs into a single HDR image.<sup>2</sup> HDR photography is not a commonly used method amongst most lighting designers. Therefore, it is necessary to evaluate the use of HDR photography as a tool to analyze lighting scenes.

## **CHAPTER 2: LITERATURE REVIEW**

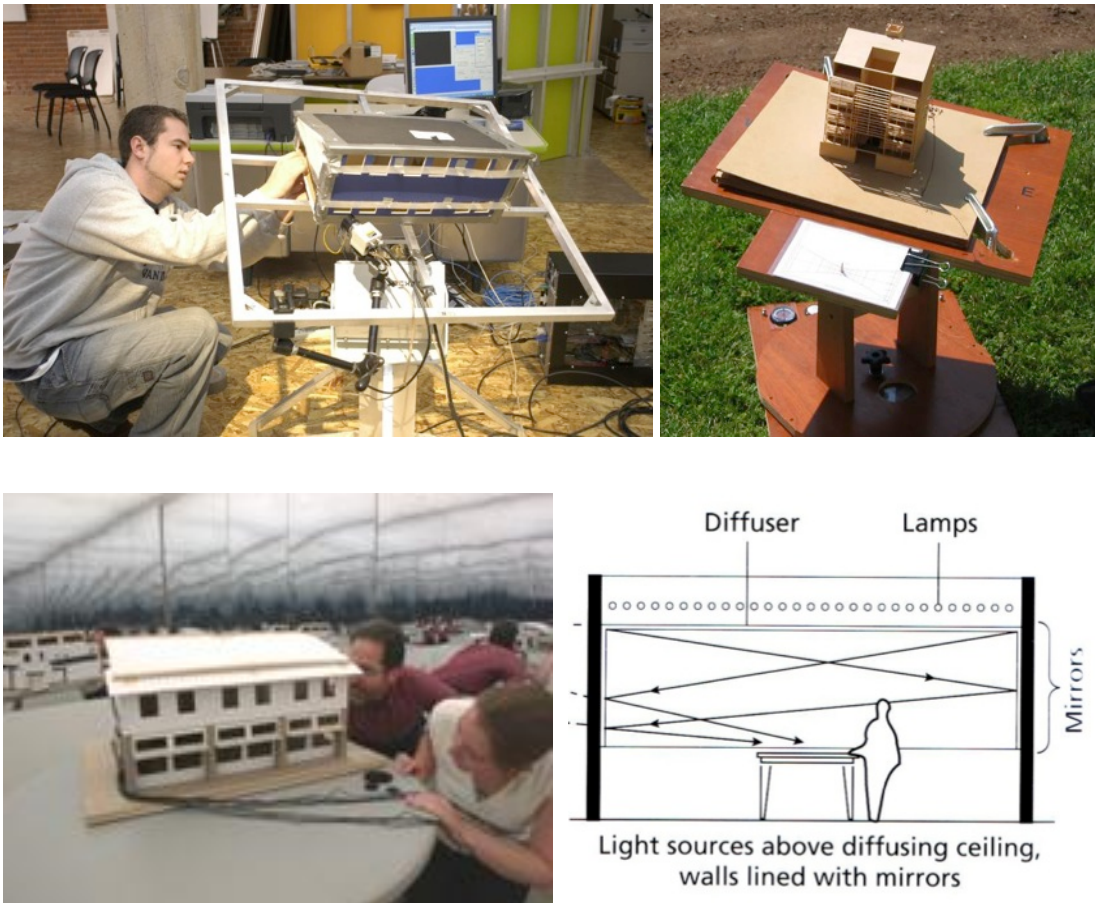
### **2.1 Use of Technologies in the Assistance of Lighting Design**

Lighting designers, architects, and engineers all have their own ways of doing lighting design. Entry-level lighting designers typically think about the space that is being designed and then search for some unique light fixtures that will provide sufficient lighting, be energy efficient, and look appealing. Designers typically then lay out the space with the light fixtures with a rough estimate of the foot-candles needed and the light fixture spacing. They create an AGI model of the space and place the light fixtures where they would like them and adjust them until they get the desired look with the appropriate amount of lighting. Once the amount of fixtures is desired, they put them in the project, circuit them and add switching and daylight or occupancy sensors as needed.

Other designers usually use other ways to design a space. Some use physical models to design a space and some have physical modeling facilities. Others make models using computer aids such as Revit, CAD, Evalglare, Radiance, DaySim, or other design software. Some examples of other types of daylighting models are shown in the following figures. Figure 2.1.1 shows a sky modeling facility that represents a real sky with real luminaires. Figure 2.1.2 shows how a heilodon simulates lighting into a space. The scaled architectural models serve as a representation of the building.

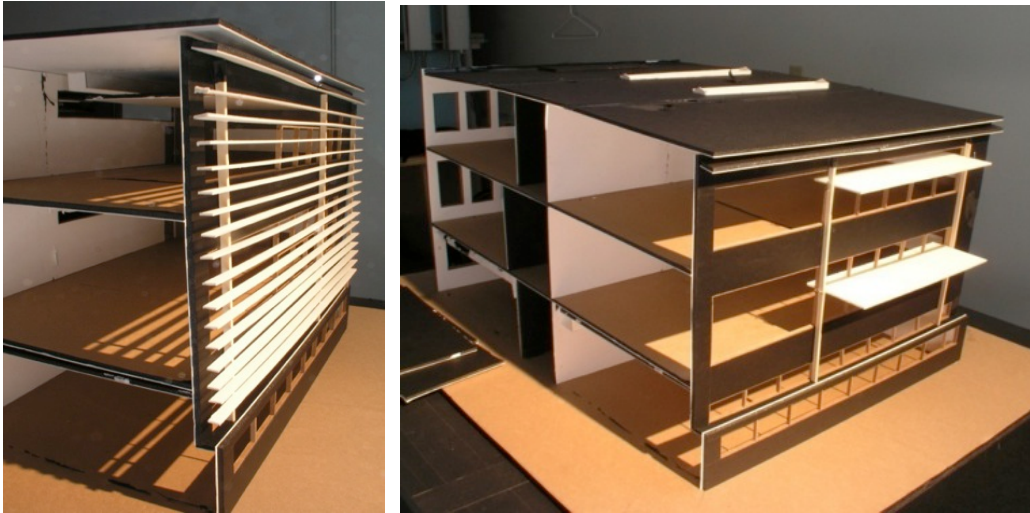


**Figure 2.1.1:** Hemispherical Artificial Sky Modeling Facilities<sup>3</sup>



**Figure 2.1.2:** Heliodon and Overcast Sky Simulator<sup>3</sup>





**Figure 2.1.3: Architectural Scaled Models**<sup>3</sup>



**Figure 2.1.4: Physical Light Measurements**<sup>3</sup>



**Figure 2.1.5: Physical Model Light Measurements Using Photography**<sup>3</sup>

The benefit of making a physical model is that one gets a real view of the space that is both reliable and accurate. However, physical models can be expensive and time consuming. Computer models are quick and low cost, have an immediate output, are easy to detail, and can combine both electric light and day light. However, computer models are not very accurate and one needs high computer skills to make a computer model.

After a space is actually designed in real life, some designers like to revisit the space to check the conditions. Some projects include redesign of an existing space. Designers, architects, and engineers typically use light meters to check the light levels in an existing space. A Minolta Illuminance Meter T-10 or T-10M is typically used or a Minolta Luminance Meter LS-100. A Fluke 117 Electrics True RMS Multi-meter or a Leica Disto D5 distance meter is sometimes used to measure the space.

Lighting measurements that use meters utilize a point-by-point process and do not account for electric lights that are non-uniform. The conventional lighting measurement tools do not provide information about the environment that the human eyes can see, such as size, shape, contrast, and color. Light that is measured by meters is inconvenient for further interpretation of lighting design because of its low resolution and limited dynamic range, although they may be specified in existing codes and standards for guiding a lighting layout. Thus, new measurement technologies are needed to help facilitate lighting design that are in line with human vision. HDR photography has been recently validated to capture a greater dynamic range of light between the darkest and lightest areas of a scene.<sup>2,4</sup> HDR photography measures an entire scene with 18 megapixels within 1 or 2 minutes and measures the luminance of target points.<sup>4</sup>



Lighting design and computer aided techniques have been widely used and research studies on lighting design and evaluation have been conducted. A lighting analysis software program known as Radiance, used by Alzoubi et al. <sup>5</sup>, was used to conduct graphical and numerical simulations for evaluating the daylight quality to facilitate lighting design. Computer-aided modeling and design in lighting have several advantages over traditional lighting techniques <sup>6</sup> because it is easy and quick to use. Computer modeling is also good for modeling details such as building facades, fenestration systems, partition walls, and it is beneficial for the use of integrating daylighting and electric lighting. As a result, free online lighting software as well as affordable and high performance computers are largely facilitated in the lighting design industry.

Aside from computer programs, photography in lighting design has the potential to be a tool to capture luminance environments within a large field of view. Film photographs have been utilized for outputs of luminance measurements in a luminous environment. In the early studies of photometry, the common approach was to acquire the calibration functions from a camera that involved very complex and lengthy physical measurements performed in laboratory conditions and required extended data analysis. The early studies were based off of a single photograph that provided a limited dynamic range of luminance. HDR photography takes multiple photographs which allows for a larger luminance range to be captured.

Photographs with different exposures are taken to capture a wide luminance variation within a scene using HDR photography. The camera-aided functions are derived from the multiple exposed photographs through a self-calibration process. HDR

photography can be done with a camera that has multiple exposure capabilities, such as a digital single reflex camera. The HDR image is fused into a single photograph from the camera response function.

## **2.2 Use of High Dynamic Range Photography**

In the past few decades, several research studies have been conducted that establish a relationship between the core aspects of lighting technologies and connecting them with good lighting design. What is considered as “good lighting design” usually takes into consideration the visibility, comfort, health, productivity, mood, and well-being of the occupants in the space. Good lighting design also considers the users circadian system, safety, occupant’s behavior, and task performance.<sup>7-11</sup> As one can see, there are many aspects to consider when one designs the lighting in a space. Lighting design also considers human factors. For example, people with vision loss would need to use more lighting and would need a bedroom with a dimmer switch.<sup>12</sup> Each space is unique and can be guided by rational applications based on existing conditions, research, and principals of design.

Some of the design principles of visual design include emphasis, order and coherence, hierarchy, unity, balance, rhythm, and color, just to name a few.<sup>13-14</sup> However, the hierarchy of focal accents in lighting design layouts is most commonly used. Lighting concepts have been commonly taught in lighting classes at the Universities, including glare and reflectance, entry of daylight, and lighting the walls. These visual concepts may be used by a lighting designer to conduct their designs.

These visual concepts were chosen as examples to demonstrate the use of the camera-aided imaging method. The visual concepts were considered in some case studies

and were conducted to create a space. Lighting tool programs such as AGI, Revit, DaySim, and Evalglare are every-day tools that are typically used by designers in a built space. Other times, physical mock ups and models of a space are created to analyze the space with regards to how the natural daylighting might fall into the space. The visual concepts that were studied are shown below.

### *Hierarchy of Focal Accents*

The hierarchy of focal points in a space is generally the order in which a user in that space perceives their surrounding environments. The people in the space get the most attention for their perceptual accent in a space, followed by movement, brightness, high contrast, vivid color, and strong pattern. Knowledge of the hierarchy of focal accents can be used to improve the lighting condition in a space. A brightly lit area in a room could be used in a way that attracts people to a specific area in a space, or can be used in a space that may need to be highlighted. This can be used to guide people's movement in a space and has commonly been used in retail or sales to attract customers. Other enhancements of lighting can be emphasized with high contrast, vivid color, and strong pattern.

### *Glare and Reflectance*

Occupants may feel discomfort glare from an extreme amount of light reflection off of a smooth surface that is reflected into an occupants' eyes which is perceived in non-uniform luminous environments. When there are non-visible cut off light sources or other bright light reflections in an occupants' view, disability glare may occur. It is

essential to avoid glare and to have ergonomic comfort in an architectural space. An architecturally lit space without glare can enhance a space and can shift the physical relationships of spatial boundaries once the environment is illuminated. A lower threshold luminance of 500-700 cd/m<sup>2</sup> in electrically lit spaces and 2000 cd/m<sup>2</sup> in daylight offices can be a potential glare source.<sup>15-16</sup> Existing codes and standards have proposed discomfort glare as shown in Table 2.1. Unified Glare Rating (UGR) measures the luminance of a lamp divided by the background of visible luminance from the room. British glare Index (BGI) evaluates discomfort glare from common non-uniform electric lighting sources. Visual Comfort Probability (VCP) is a percentage of people that will find a certain scene comfortable with regards to glare. Discomfort Glare Index (DGI) is the first formula put forth to calculate perceived glare from daylight. It is applied with the observer facing the daylight aperture and the produced results are “just perceptible” and “just intolerable.” Daylight Glare Probability (DGP) is more recently introduced with a probability output similar to DGI. It is based on vertical eye illuminance that may correlate better with the human subjects response.

**Table 2.1:** Scales of Discomfort<sup>5, 17</sup>

Semantic criteria	UGR/CGI	BGI	VCP <sub>CIE055</sub> (%)	DGI	DGP
Intolerable	34	31	12	30	
Just intolerable	31	28	20	28	
Uncomfortable	28	25	28	26	
Just uncomfortable	25	22	36	24	
Unacceptable	22	19	43	22	0.45 or higher
Just acceptable	19	16	50	20	
Perceptible	16	13	59	18	0.4
Just perceptible	13	10	67	16	
Imperceptible	10	7	75	14	0.35 or less

### *Entry of Daylight*

The first factor that is considered while creating a lighting design is the presence of daylight. Intentionally placed light shelves and reflective panels in building fenestration systems can be placed to receive more daylight in an architectural space. Daylight may also be diffused through perforated glass or can be screened with decorative architectural grilles on the building. In the deeper spaces, supplemental electric lighting is often used to create specific moods and to stimulate natural light. The challenge is to mix natural daylighting with supplemental daylighting and integrate them together without causing glare or unwanted hot spots. Daylighting should be integrated and controlled to have an even illumination throughout a space.

To evaluate daylight performance in building interiors, the daylighting factor (DF) is used. The DF can not be used to evaluate a user's visual perception of daylight in a luminous environment.<sup>18</sup> An average DF of greater than or equal to 5% is known for daylight spaces, partially daylight spaces have an average DF in between 2-5%, and non-daylit spaces have an average DF of 2% or less.

### *Lighting the Walls*

In commercial interiors, lighting the walls is very common in architectural spaces, particularly to attract attention to the users. Higher brightness on the walls in an architectural space usually adds a feeling of spaciousness. Control of non-uniform brightness and its spatial distribution on the walls is critical because it relates to the perception of the occupants visual comfort and the perception of the ambient environment.<sup>19</sup> Wall grazing and wall washing are two techniques commonly used for

lighting different types of walls. Wall washing is typically used to light a wall uniformly from the top to the bottom and can be used to eliminate shadows, hide imperfections, to show the vertical boundaries, or to make the wall outstanding from the ambient environment. Wall grazing can also be used to emphasize textures on a wall such as stone, wood, or brick. Ceiling mounted wall washers are mounted closer to the walls to produce shadows that reveal textures.

Spatial distribution of luminance gradients across an architectural space could be mapped and generated from HDR images.<sup>20</sup> The recommended luminance ratios between a task and its immediate background are 3:1 or 1:3 or lower. HDR images can be used to analyze an existing space and to help understand what type of lighting design is needed in a space.<sup>21</sup>

Some simple visual concepts that may aid in lighting design are the hierarchy of focal points, glare and reflectance, entry of daylight and daylighting the walls. A good lighting design needs to consider the human response and the appearance of the space while considering the visual environment and visual function.<sup>22</sup> The correlated color temperature (CCT) specifies the color appearance of light in terms of warmth or coolness. Several different research studies were conducted to explore different technologies and their impact on lighting design.<sup>23-26</sup> Loe et al.<sup>27</sup> suggested minimum values of 30 cd/m<sup>2</sup> for two parameters that have visual interest. Hue et al.,<sup>28</sup> did not find any correlation between the Correlated Color Temperature (CCT) of lamps and the perception of interior brightness. Also, Davoudian<sup>29</sup> found that the visual saliency of illuminated urban objects could significantly be reduced by increasing background lighting. Lighting

practice should be based on luminance contrast between two different representative surface elements as mentioned by Moeck.<sup>30</sup>

Cai et al.<sup>31</sup> mention that the first stage in the lighting profession (1898-1945) was based on uniform illumination over a horizontal plane, which is still used today.<sup>32,33</sup> Since 1945, the objective of the lighting profession was to provide illuminance-based metrics for visual performance in an architectural space. Lighting levels for general applications should deal with human vision<sup>34</sup> and luminance-based light measurements that are based on visibility requirements.<sup>32,35</sup> It was found that the threshold value causing discomfort glare would be much higher due to the increased adaption level of occupants' eyes.<sup>36</sup>

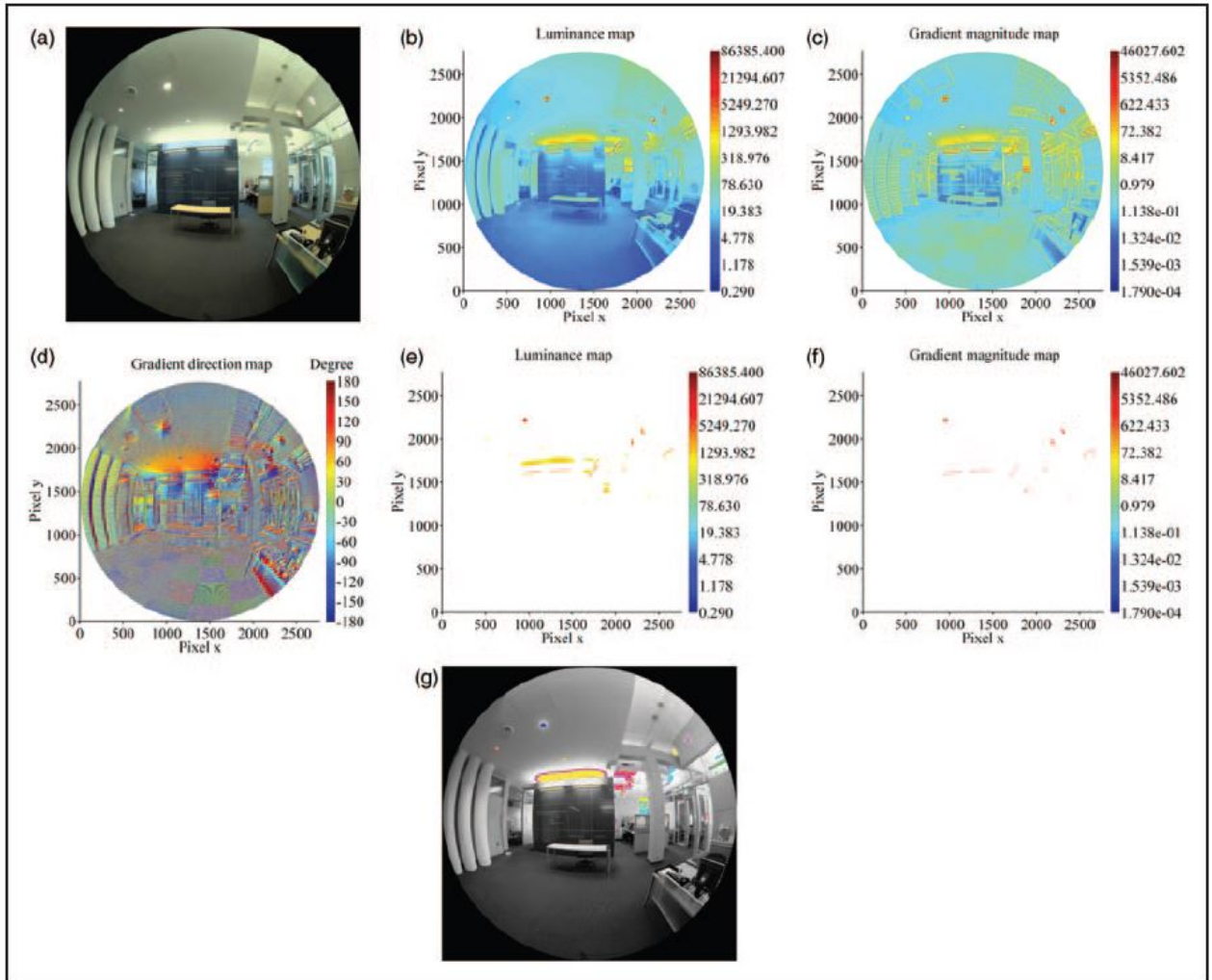
In the paper written by Cai et al.,<sup>31</sup> four case studies were conducted to demonstrate the use of HDR photography for the evaluation of interior lighting environments. The case studies conducted analyzed the core visual concepts of lighting design that include hierarchy of focal accents, points of glare and reflectance, entry of daylight, and lighting the walls. Each test scene represents the four visual concepts while also looking at the general visual concepts of lighting design. The four case studies shown were taken at the University of Kansas in the architecture administrative office Marvin Hall, the entry Spahr Library, the computer lab in Eaton Hall, and the grand stair entry in Eaton Hall. The following case studies are as follows and are referenced from the paper Case Studies of a Camera-Aided Imaging Method for Evaluation of Interior Luminous Environments written by Cai et al.<sup>31</sup>:

*Marvin Hall – Architecture Administrative Office*

In Figure 2.2.1, the lighting in the space seems to be okay without any obvious problems when one takes a glance at the space. However, after the HDR images were conducted, one can see that many improvements can be made to the space. The ideal lighting design in this space would need an emphasis on the receptionist's desk, would need to highlight the school logo, and provide efficient and good lighting to the workers in the office space. As one looks at the HDR images and the luminance maps, one can see that the school logo is not highlighted properly and the pendant lights over the receptionist desk do not draw enough attention as needed. The focal points in the luminance map seem to indicate that the office windows are the brightest points in the space. Many highlighted spots in the space are brighter than the threshold value of 500  $\text{cd/m}^2$  and may cause luminance glare, as shown on the HDR images.

A designer might look at the images and think of better ideas to light the office space. The school logo, for example, could be highlighted in a different way by using an LED strip hidden in a cove. The front desk could use a little more light to attract students. Also, the ceiling lights can be re-arranged to get a more even illumination in the space.



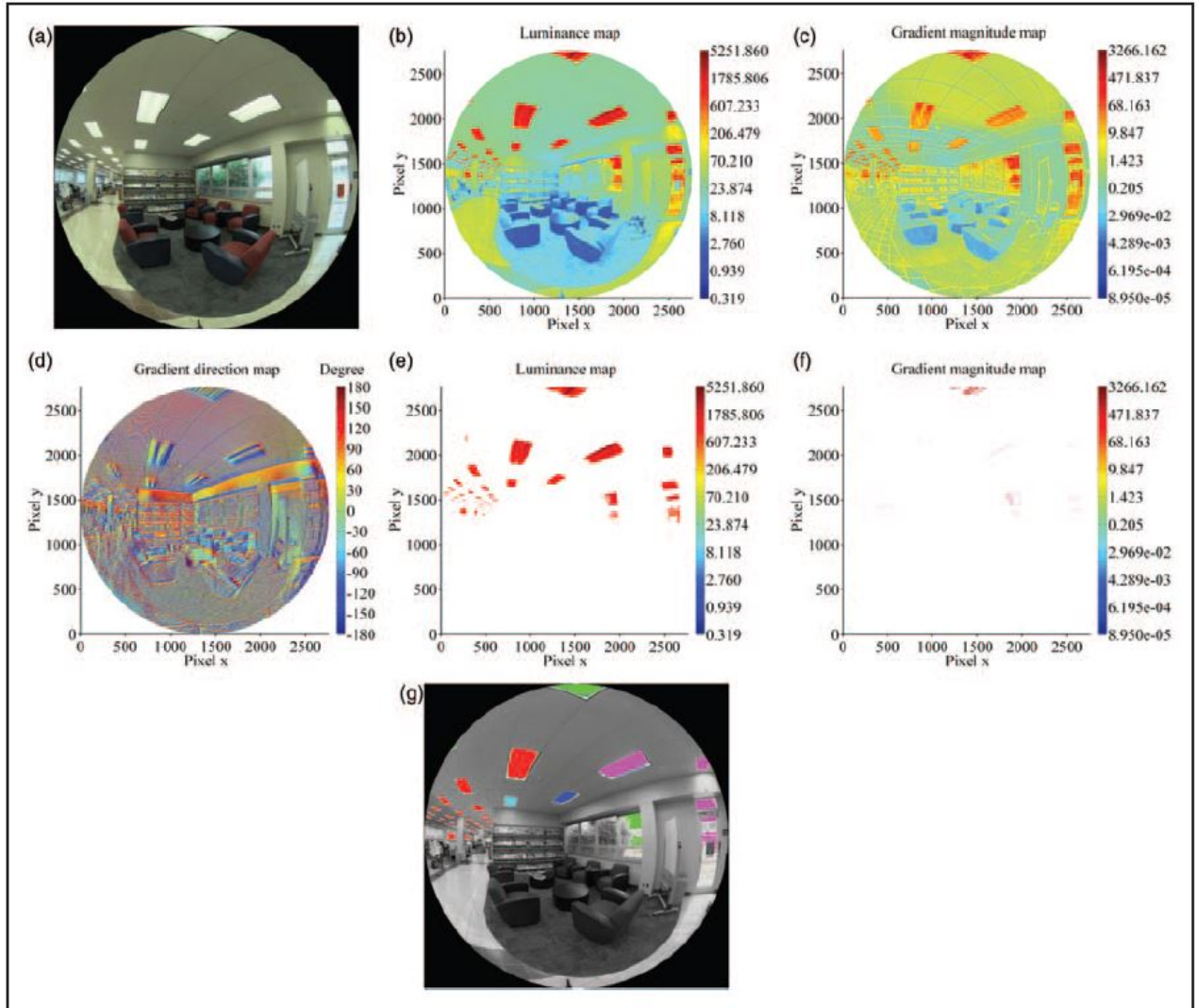


**Figure 2.2.1:** Marvin Hall – Architecture Administrative Office <sup>31</sup> (Cai et al., Figure 1)

(a) HDR Image of the space with windows facing west (b) luminance map (c) 2D  
luminance gradient magnitude map (d) 2D gradient direction map (e) the luminance map  
filtered with the lower threshold value  $500 \text{ cd/m}^2$  (f) 2D luminance gradient magnitude  
map (g) the potential glare sources marked on the HDR image by Evalglare

### *Spahr Library – Entry Area*

In Figure 2.2.2 a seating area in the Spahr engineering library was photographed and is typically used by students as a temporary seating area. The windows in the space faces south; however, most of the daylight is blocked from the south sky from another building outside. There is an adequate daylighting control of the windows from the shading blinds. As one can see from the luminance gradient maps, most of the potential glare comes from the standard 2x4 foot (.61m x 1.2m) electric light fixtures in the space. Looking at the luminance map, one can see that the lighting near the magazine rack has an even illumination. A uniform ambient-lit environment is shown in the pseudo color image located between the ceilings and the walls that could make the room feel more spacious.



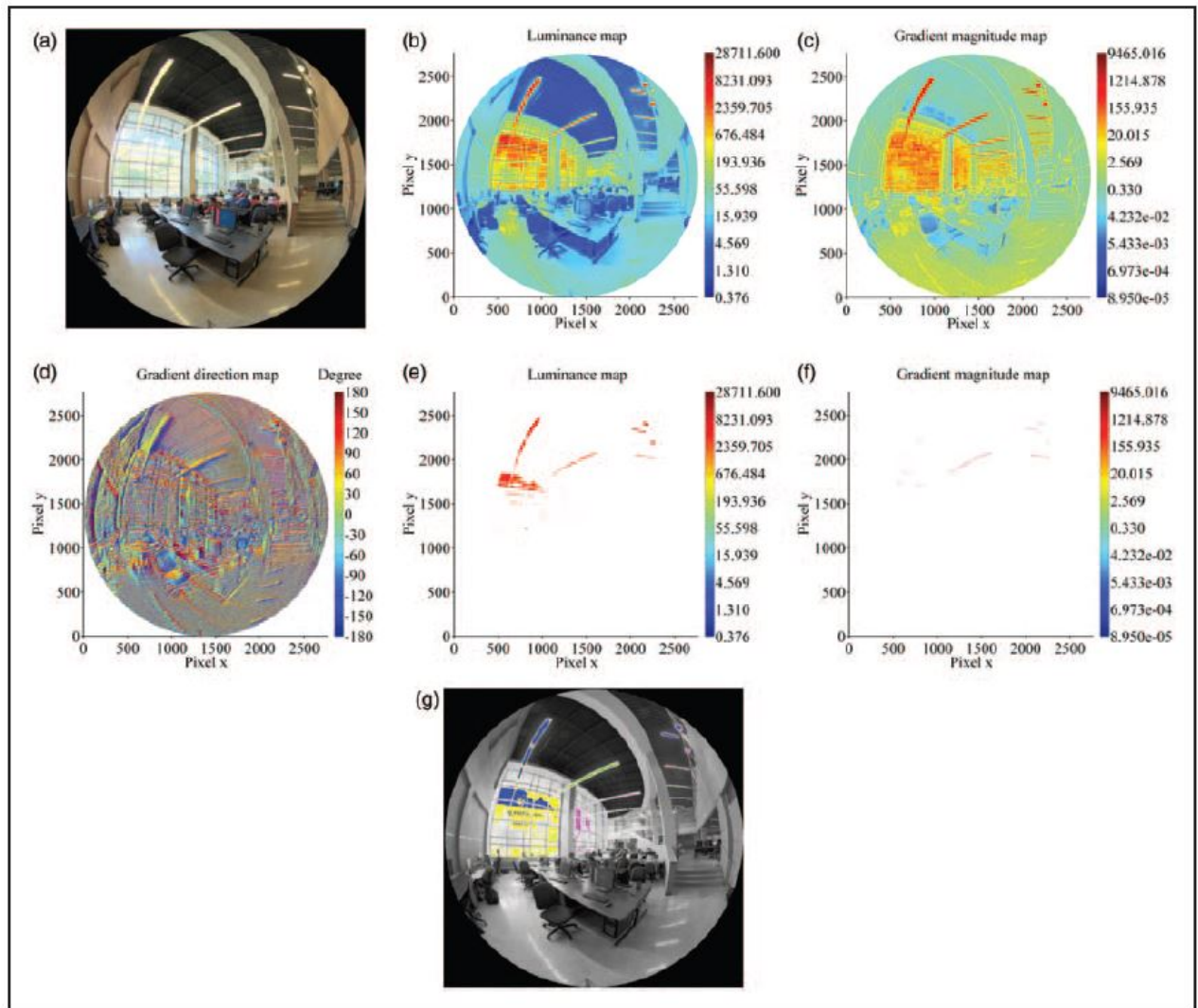
**Figure 2.2.2:** Spahr Library – Entry Area<sup>31</sup> (Cai et al., Figure 2)

(a) HDR Image of the space with windows facing north (b) luminance map (c) 2D luminance gradient magnitude map (d) 2D gradient direction map (e) the luminance map filtered with the lower threshold value  $500 \text{ cd/m}^2$  (f) 2D luminance gradient magnitude map (g) the potential glare sources marked on the HDR image by Evalglare

### *Eaton Hall – Computer Lab*

In Figure 2.2.3, a computer lab was photographed that has a large open space filled with computers often used by students. One can see from the HDR images that there is an even illumination around the space provided by the electric lighting; however, there is glare caused from the main glass curtain wall. To identify the potential glare sources, a threshold value of  $2000 \text{ cd/m}^2$  was used. As one can see from the luminous maps, the fluorescent linear fixtures have both high brightness and dramatic luminous changes and the glaring window patches have high brightness but a mild variation of lighting.

Laying out the computers perpendicularly to the window is a good solution so that the bright light coming through the window and the electric lighting is not visible or does not cause glare on the computer screens. To prevent potential glare, one can add window blinds or transparent shades to the large window wall. Another option would be to use indirect lighting or cover the current electric lighting with a diffused lens.



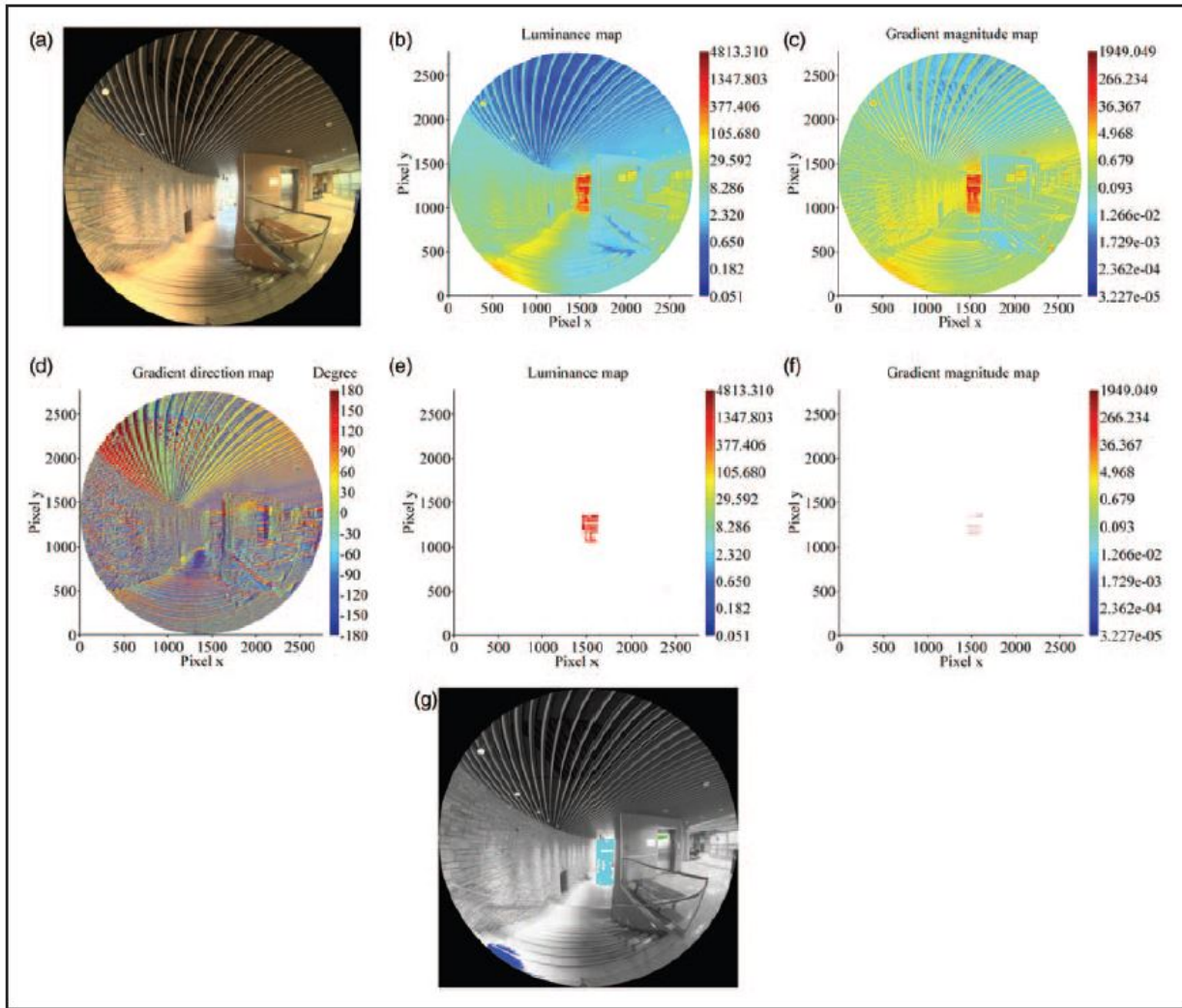
**Figure 2.2.3:** Eaton Hall – Computer Lab <sup>31</sup> (Cai et al., Figure 3)

(a) HDR Image of the space with curved northwest facing window curtain wall (b) luminance map (c) 2D luminance gradient magnitude map (d) 2D gradient direction map (e) the luminance map filtered with the lower threshold value  $2000 \text{ cd/m}^2$  (f) 2D luminance gradient magnitude map (g) the potential glare sources marked on the HDR image by Evalglare

### *Eaton Hall – Grand Stair Entry*

In Figure 2.2.4, a reception area that is often used for events was photographed. A large window wall faces south at the main entrance. Extreme luminance changes and high brightness occur where there is entry of daylight. Figure 4 (e) and (f) show potential discomfort glare near the entry area of daylight. Looking at the 2D gradient direction map, one can see that there is a large amount of well-disused light in the space. One can also see that there might need to be more lighting at the staircase area. A solution would be to use a linear high contrast stair lights so that there is more contrast at the edge of the steps to make them safer to use. Also, the wall-washers in this space are not efficient enough since it seems that most of the light is not washing the wall, rather falling on the floor. The lighting on the walls needs to be stronger to make a better impact for the users as they use the space.





**Figure 2.2.4:** Eaton Hall – Grand Stair Entry<sup>31</sup> (Cai et al., Figure 3)

- (a) HDR Image of the space with large glass wall facing the south at the main entrance  
 (b) luminance map (c) 2D luminance gradient magnitude map (d) 2D gradient direction map  
 (e) the luminance map filtered with the lower threshold value 500  $\text{cd/m}^2$  (f) 2D luminance gradient magnitude map (g) the potential glare sources marked on the HDR image by Evalglare

The HDR imaging method in these case studies was found to be useful in order to evaluate luminous environments. The case studies looked at the four different visual concepts that were mentioned previously. As one can see from the HDR images, some spaces were well lit while others needed some improvements. This method can help facilitate the understanding of lighting design in common lighting applications. HDR photography could potentially be very beneficial for lighting designers aside from using the lighting standards and computer aided programs. HDR photography can help aid designers to really understand a space. Many research studies have shown the multiple benefits of using HDR photography as a tool for designers.

### **2.3 Research on HDR Photography and the HDR Imaging Method for Lighting**

#### **Measurement**

There is a trend of computer-aided lighting evaluation in line with observers' visual perception using HDR images of interior and exterior luminous environments. The values in HDR photography represent real-world luminance rather than arbitrary pixel values. The paper reviews some of the technologies used to achieve real world accuracy with HDR images. There have been many advances in digital camera technologies, but one major problem with digital cameras is the ability to capture scenes as they are viewed in real life. Recent advances in HDR photography show how the potential limitations can be overcome.

The 10<sup>th</sup> edition of the Illuminating Engineering Society (IES) lighting handbook includes a new procedure for determining target illuminance and has introduced further categories with finer steps to allow adjustment of luminance requirements, considering



factors such as minimum, average, or maximum target values, uniformity targets, occupant's age, and adjustment of photopic/mesopic adaption.<sup>37</sup> The modern lighting profession is expected to transform from assessing light incident on planes to assessing light arriving in the eye.<sup>32</sup> Corresponding lighting criteria and evaluation methods, such as the camera-aided imaging method developed by this study, would evaluate the seeing process in the real space with design options to interpret the individual differences.<sup>35</sup>

Real scenes in real visual environments have a large dynamic range between the excess of 100,000 to 1 between the brightest and darkest areas. Digital cameras are only able to capture a small portion of that range. This limits the ability to capture an accurate HDR image and it also may cause highlights in the image from spillover effects. Another camera limitation is that the shutter speeds may not be as accurate as the settings on the camera mention. For example, 1/30<sup>th</sup> on the camera settings might actually be 1/32<sup>nd</sup>. These errors add up and the results may not be very accurate.

When the images are taken, they are not always aligned. To get accurate and clear images, a tripod must be used, which may be difficult for an average lighting designer to use, unless they are in laboratory type situations. The camera's response curve can only be determined if the images are perfectly aligned. The most common alignment operations are based on edge detection or a mean pixel threshold. The use of an alignment operator based on the median of the pixel values to avoid the images being unaligned was proposed by researchers.

Photometric calibration can be done by comparing the HDR luminance with readings taken in the real scene with a spot luminance meter. The ratio between the HDR image and the luminance meter may be used as a calibration factor for the images. When

an HDR image is taken using a wide-angle lens, a more thorough luminance calibration can be taken into account by using the vignetting effect.

HDR imaging still has a long way to go before becoming a generally accepted tool to be used by consumers. The desirable end-goal would be to have HDR images without requiring any post-processing and make it an easier tool to use.

Inanici<sup>7</sup> studied the limitations and applications of HDR photography evaluated as a luminance mapping tool. Camera response functions were derived from HDR images using Photosphere software. Laboratory measurements showed that pixel values in HDR photographs correspond to the physical quantity of luminance with reasonable accuracy.

Vignetting is strongly dependent on aperture size and increases dramatically with apertures that are wider. For the study conducted, a separate polynomial function was derived to fit into each RGB channel into Photosphere. Inanici<sup>7</sup> showed that HDR photography is a useful tool for capturing luminance over a wide range with 10% accuracy. Although HDR photography may be useful, it is not a substitute for luminance meter measurements.

Inanici<sup>7</sup> studied the application of HDR photography and its technique is evaluated as a luminance mapping tool. The study concludes that HDR photographs indicate reasonable accuracy compared to physical measurements. However it is not a substitute for physical measurements. It provides a measurable capability that captures high-resolution luminance data within a large field of view quickly and efficiently, which a typical luminance meter cannot achieve.

The self-calibration algorithm in Photosphere provides response functions that are quick and easy in comparison to the lengthy calibration measurements required in

previous studies. A HDR image can be post-processed to simulate human visual sensitivity, studied for visual analysis, and used for presentations of an existing space.

Cantin<sup>38</sup> recognized the advantages of natural light and how it can have great benefits to the occupants and their circadian systems. Despite the fact that daylighting has many benefits, it is still not most commonly used for lighting. The use of daylighting may be due to a lack of informative daylight performance indicators or because over optimistic energy saving predictions are not realistically met in real buildings. Cantin<sup>38</sup> attempted to look at the limitations of daylighting and contribute to the ongoing discussion about daylighting metrics. The methodology proposed was based on the computation of various daylight metrics related to illuminance, distribution, glare and directivity.

Cantin<sup>38</sup> assessed the quality of daylight in two office spaces located in downtown Montreal, Canada. One office was oriented in a south-west position and the other in a north-west position. Traditional evaluations of lighting conditions usually focus on the horizontal illuminance. The daylight factor (DF) is insufficient due to its limitations such as the fact that DF cannot be considered in non-overcast sky conditions, it does not consider the building or room orientation, and the effect of mixed natural and electric lighting cannot be quantified. New daylight metrics state that the main parametrics determining the luminous environments are the luminance distribution, illuminance, glare, directionality of light, color rendering, flicker, and daylight.

The study done by Cantin<sup>38</sup> was carried out using Radiance Lighting Simulation and DaySim. DaySim uses the daylight coefficient method to calculate illuminance distributions under all sky conditions. The luminance ratios were calculated for an

occupant sitting at the computer and doing paper tasks for each office. The Radiance program p<sub>value</sub> was used to obtain the luminance values of each pixel of the fish-eye image corresponding to the direction the user looks. The study shows that there was a risk for over lighting and glare in both office spaces. The Useful Daylight Illuminance (UDI) risk was generally slightly higher in the south-west office for paper tasks. Low DGP values were more sensitive to the presence of direct sunlight than when under diffused lighting.

The study done might have been improved if the computer-based assessments could be compared to real life situations. Another limitation was the use of clear skies instead of variable sky conditions. A further step to improve the previous study is to integrate both electric and daylighting into one study.

With regards to ergonomic design at workplaces, there is not standard procedure that monitors daylighting that establishes a basis of glare evaluation on a comparative bases under real sky conditions. Nazzal <sup>39</sup> introduced a new glare evaluation method that consists of a standard monitoring protocol for window luminance, adaptation luminance, exterior luminance and a formula for solid angle for the configuration factor of a window.

The glare evaluation procedure was developed so that lighting designers and architects would adopt this procedure to have a reliable method for evaluating discomfort glare from daylighting. The study done by Nazzal showed that sky luminance usually has a significant influence on discomfort glare. Nazzal proposed that discomfort glare can be predicted mathematically and that reliable data for lighting control can be derived from DGI.

Konis et al.<sup>40</sup> used the HDR images for prediction of visual comfort of interior and exterior shading systems for commercial buildings. They used the Radiance program commands *findglare* and *glareindex*<sup>41</sup> to detect glare sources on the HDR images and compute their daylight glare index (DGI) values. Wienold and Christofferson<sup>17</sup> derived a new daylight glare prediction model, daylight glare probability (DGP), that is based on HDR data correlated to subjective response. They defined glare as any pixel with four times greater luminance than the average luminance of a circular visual task zone. Wienold<sup>42</sup> developed a radiance-based program, Evalglare, for calculating DGP and other common discomfort glare indices like DGI, unified glare rating (UGR), visual comfort probability (VCP), and Commission International de l'Eclairage (CIE) glare index (CGI). Howlett<sup>43</sup> studied the subjective distraction effect of glare on display screens and noticed that the tolerable level of luminaires exceeded 2000 cd/m<sup>2</sup>.<sup>44</sup>

Howlett et al.<sup>45</sup> investigated several potential luminance-based daylight metrics using HDR luminance maps of test spaces for quantifying the discomfort glare metric specific to daylight, including normalized UGR, luminance variation, ceiling variation, back wall brightness, window contrast, directionality, and luminance DF. Recently, Bellia et al.<sup>46</sup> proposed a software program with the aid of the HDR imaging technique to analyze the most significant factors that influence the lit environments' perception for visual comfort and energy saving. The proposed camera-aided method in this paper is one more example of this trend.

Glare can be divided into three types of glare: reflex glare, disability glare, and discomfort glare. Discomfort glare is a subjective rating that can have indirect consequences such as headaches and fatigue and is often not directly measurable.

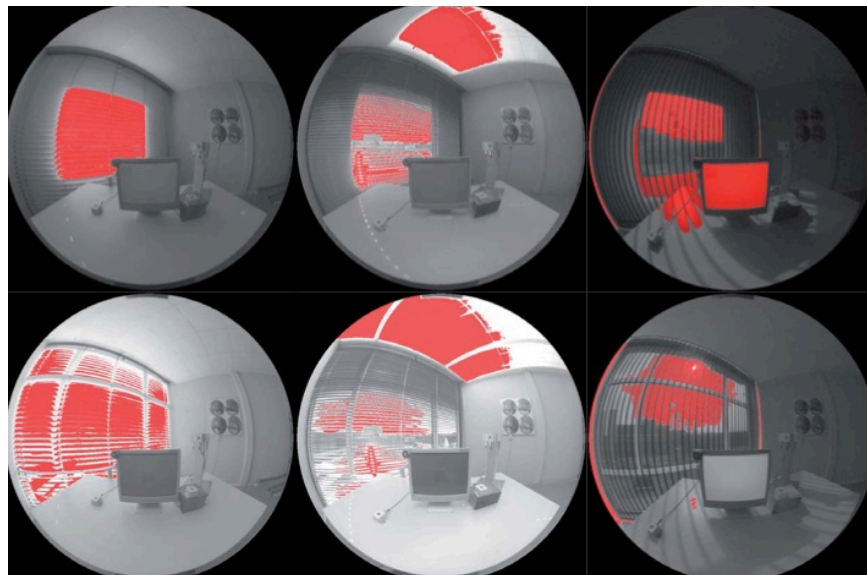
Wienold <sup>42</sup> conducted three case studies where shading devices were tested. The metrics were compared to the percentage of a person being disturbed by glare. The new tool Evalglare is used to evaluate existing glare measures as well as the basis from the development of new glare reading methods. The results of the study were compared and correlated to user assessments. The user assessment data is processed in a way that for each situation, the outcome is a binary variable indicating if the subject is disturbed by glare or not. This disturbance is compared to the glare measured by the use of logistic regressions. As a result, the existing glare rating models show moderate to poor correlations with the users perception of glare.

The first glare detection method as shown in Figure 2.3.1<sup>42</sup>, shows brightness on the images, with only a few parts of the glare source, or none can be detected. Reducing the x-factor can increase the sensitivity to detect glare sources in a specific scene, but leads to a strong potential of over detecting glare sources in darker scenes. Wienold (Wienold et al. <sup>42</sup> Figure 6.7) applied a glare detection method on these images with an x-factor of 4. The red colored pixels are the detected glare potential glare pixels, which should be treated as a glare source.

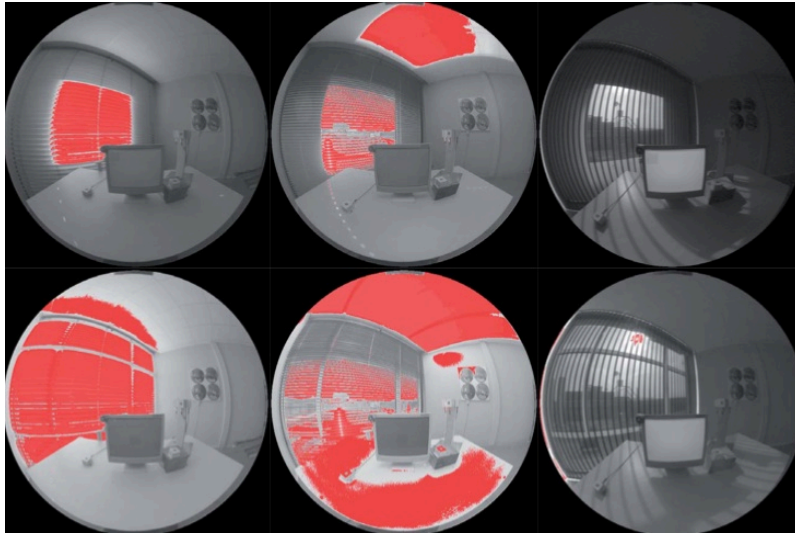
The second method shown in Figure 2.3.2, which applied a fixed luminance value as a threshold, does not take the adaption of the human eye into consideration. This method can detect glare pixels properly in many cases, but fails in particular with bright images due to over detection. This method is therefore not considered to be a reliable method for evaluating lighting scenes with substantial luminance variations. Wienold (Wienold et al. <sup>42</sup> Figure 6.7) applied a glare detection method on these images with a x-

factor threshold of 2. The red colored pixels are the detected glare potential glare pixels, which should be treated as a glare source.

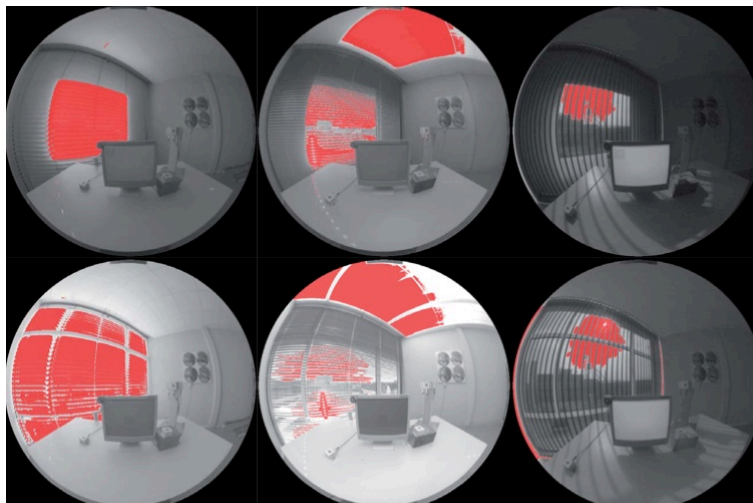
The third method shown in Figure 2.3.3 used task luminance as a threshold for the glare source detection. The task zone is chosen so that it covers most parts of the computer screen and parts of the value x-times higher than the average task-zone luminance as treated as a glare source. Wienold (Wienold et al. <sup>42</sup> Figure 6.7) applied a glare detection method on these images with a threshold value of 2000 cd/m<sup>2</sup>. The red colored pixels are the detected glare potential glare pixels, which should be treated as a glare source.



**Figure 2.3.1:** Case Study 1 by Wienold <sup>42</sup>



**Figure 2.3.2:** Case 2 Study by Wienold <sup>42</sup>



**Figure 2.3.3:** Case 3 Study by Wienold <sup>42</sup>



Evalglare is a tool that detects glare sources within a given image and calculates the glare indices such as DGP, DGI, CGI, UGR and other important values (solid angles of sources, vertical illuminance, and a number of glare pixels) which can also be used for other image evaluations. Evalglare uses images in the radiance image format, which enables its users to evaluate simulated scenes. For these studies, after the glare detection, these glare source pixels were merged into larger areas of glare sources if the distance between the glare pixels is small. There is no glare source size limit and no automatic subdivision of glare sources implemented into Evalglare.

Evalglare calculates the average luminance, the solid angle, and the position within the image for each found glare source. With these values, the validation with existing glare indices can be processed. The question is what to identify as a potential glare source. Three principal methods are tested for the automatic detection of glare sources. The first is to calculate the average luminance of the entire image, counting every section as a glare source that is  $x$ -times higher than the average luminance. The second is to take a fixed value and count every section as a glare source that is higher than the fixed value. And third is to calculate the average luminance of a given zone or task area and to count every section as a glare source that is  $x$ -times higher than the average luminance of the zone.

A study done by Cai et al.<sup>31</sup> was driven by the existing research gap on measurement and evaluation of common non-uniform luminous environments. The study introduced the luminance gradient for an evaluation of a wide variety of luminous environments in extremely high resolution (millions of pixels) in line with the visual perception of the observer. Conventional light meters are not always suitable for

measuring non-uniform luminance distributions and changes over a space. HDR photography could be used to measure per-pixel luminance of an entire environment, but the technology still cannot simulate human vision.

The study provided technical solutions to bridge the gap. The study redefined the luminance gradient to consider the luminance measurement at different points in practice with two units:  $\text{cd/m}^2/\text{pixel}$  if it is measured with a camera or  $\text{cd/m}^2/\text{foot}$  if it is measured using a luminance meter mapped via geometric XYZ coordinates. The study also developed a new method for visualization of luminance gradient using 3D images in x,z coordinates. The study also developed the MatLab code for mapping luminance gradients in different applications. Users can identify potential lighting hazards such as bright spots, extremely high contrasts, or large non-uniform window shadows. These potential lighting hazards usually have higher values than the lower threshold.

The study by Cai et al.<sup>31</sup> found that luminance gradient data across a luminous environment could be obtained from computer simulation software such as AGI or HeliosPro. However, the simulation results may have large errors compared to HDR field measured photographs.

HDR images can be converted to luminance maps with a camera response curve; however, the results from a consumer grade camera have shown luminance errors as a function of Munsell hue and value. Two problems occur with measurements taken from a digital SLR camera with CMOS sensors. The first problem is that saturated hues, especially blue, green, and purple, are difficult to measure. The second problem is that surfaces with low reflectance below the Munsell value of N4 can significantly be overestimated.

Moeck<sup>47</sup> had mentioned that there are disadvantages of fisheye lens. Some of the disadvantages are the cost, vignetting, and lens flare. HDR imaging can be a useful tool but it is recommended to get a series of gray cards and matte color checkers with known reflectance and uniform illuminance. The luminance can be reasonably estimated from most hues and values. Dark surfaces are usually over estimated and light surfaces are underestimated.

Wide angle lenses typically used for HDR images produce a barrel distortion. The lens distortion affects the luminance mapping as well as perspective rectifications. The distortions created by lenses can be corrected by applying suitable algorithmic transformations to the digital photograph. To reduce lens distortions, one may use a small-angle lens such as a telephoto lens. Lens distortions should use polar coordination systems.

The ideal perspective mapping should map real world straight lines to straight lines in the image. Calibration programs mostly use a rectangular grid of straight lines, like a checker board, to generate a set of equations and then calculate the mapping parameters with a non-linear least squares fit measurement. The effects of tangential distortion are mostly negligible. The distorting effects created are specific to an individual's camera and cannot be eliminated by a database.

Digital cameras have several physically distinct sources of noise. Some include shot noise that comes from the fact that everything in the universe has particles. Thermal noise is created from random tunneling from temperature. Other noise occurs such as conductive noise, pixel noise, and read noise. These noises need to be considered when taking an HDR image.

Mistrick et al.<sup>48</sup> tested a new method of lighting controls by using an inexpensive image sensor as the light sensing device in conjunction with HDR imaging. A single sensor is capable of estimating the illuminance levels at multiple locations on a work plane. Photo sensor-based systems have limited applications and various problems with calibration contribution. Mistrick et al.<sup>48</sup> developed a concept to compute luminance at various locations in a room and used the information to adjust the luminaire output to maintain a desired illuminance level.

What they found in their study is that camera-sensing technologies are feasible for lighting control with digitally addressable ballasts. Surface reflectance creates the need to calibrate the control system for each separately controlled light source. Also, some cameras have difficulty dealing with low luminance and a proper system layout is necessary to achieve optimum lighting controls.

Goesele et al.<sup>49</sup> proposed a daylighting dashboard that meets eight design goals: average illuminance, coverage, diffuse daylight, daylight autonomy, circadian stimulus, glazing area, view, and solar heat gain. The most critical decisions for capturing daylighting come from the conceptual phase of architectural design when the configuration of the building is formulated.

The daylighting dashboard conducted by Leslie et al.<sup>50</sup> was created for conceptual designs only. The purpose of the daylighting dashboard is to be able to compare the potential of alternative design solutions to achieve the eight daylighting goals before the space is completed, in order to still have an opportunity to modify the form, orientation or glazing of the building. The daylighting metrics developed have since disagreed on

factors such as accuracy versus convenience and what information is necessary to guide performance evaluation.

## **2.4 Research Gap**

Often times, lighting specialists, designers, and engineers create a unique luminous environment because they think it looks great. Although the design may meet the requirements of codes and standards, what may be lacking is the relevant principles of visual design and the supporting technologies behind those creative ideas. Such principles and concepts are adopted in lighting design in line with the occupants' visual perception of the luminous environment, and thus are closely related to the spatial luminance distribution across a space.

To interpret the design in light of the visual principles and concepts, luminance-based metrics (target luminance, background luminance, adaption luminance, ambient luminance, luminance contrast, luminance gradient) need to be measured in the given building environment. Nonetheless, conventional lighting design is mainly based on the amount of light needed in a space. Illuminance based metrics (e.g, horizontal illuminance, vertical illuminance, task area illuminance, daylight factor, daylight autonomy) are predominant in codes and standards. Since human eyes detect luminance, not illuminance, such illuminance-based metrics cannot be used for interpreting lighting design in visual concepts. To handle this, well-experienced lighting professionals have gained empirical knowledge through many years of lighting practice. However, what if an existing space needs to be renovated?

HDR photography acquires spatial luminance distribution of an entire luminous

environment in extraordinarily high resolution. Unfortunately, there lacks an intuitive and efficient method that adopts HDR photography for designers to analyze the creative aspects of lighting design that follow any visual principals and concepts and to guide their use of supportive lighting technologies.

Some questions that may be asked with regards to the use of HDR photography follow: What is the point of using Evalglare and how can a designer use the information that is gathered from this program? Can the program be made easier to use and easier to understand? Can Evalglare give tips to the designer as to what to do if there is glare in the space? Can a program like AGI be incorporated with Evalglare to show designers potential problems before the space is designed? Is there an easier way to take HDR images, especially if the designer does not have all of the equipment needed? Why would Evalglare and HDR photography be useful if the space already exists that is being studied?

As a lighting designer in the field, HDR photography does not seem like a typical tool and is not easy enough to use. Other lighting designers, architects, and engineers may feel the same way too. The question is, can HDR photography become a common tool to use to evaluate existing spaces? Perhaps HDR photography can be made easier to use or a program can be created that a designer can place an image into and a HDR image comes out. There also needs to be an easier way to look at the luminance and gradient maps to evaluate the existing conditions. The designer also needs to understand the metrics as they are looking at the image and what they mean.

Designers usually use programs such as Revit or AGI or Visual to make a design. Perhaps integrating HDR photography into these programs would make it easier to use.

HDR photography might even be made into a phone application where the designer can simply take a picture and produce an HDR image with all of the simple information that a designer needs to understand. Since most designers are visual people and have creative minds, making the HDR image more aesthetic might appeal to designers.

At the moment, HDR photography might be difficult for a traditional lighting designer to use. In fact, they might ignore this tool all together because the method is too time consuming and can be difficult to understand once the images are generated. The goal of this study is to bridge the gap between the tool and its use, ultimately making it easy for designers in the field to use.

## CHAPTER 3: METHODOLOGY

### 3.1 A Protocol of Using HDR Photography in the Professional Lighting Design

#### Practice

The basic steps for taking an HDR image are shown below. Step by step instructions and screen shots are shown for basic production of HDR images. A questionnaire was formed which showed six graphs that contained luminance maps, gradient maps, or gradient direction maps. The questionnaire was sent out to professionals who have beginning to high-level experience in the lighting design field. The feedback was processed through an online survey and then analyzed in percentage of how many designers answered yes-or-no. The results were then analyzed to understand the efficiency of the camera-aided design method. Four case studies were then conducted to validate the application of the imaging method in the lighting design field.

The basic steps of taking HDR images and using them for data analysis are as follows. A more detailed list of the procedure is shown in chapter 3.4.

*Step 1:* Take low dynamic range (LDR) images.

*Step 2:* Convert the LDR images into a single high dynamic range (HDR) image.

*Step 3:* Calibrate the HDR image.

*Step 4:* Plot the luminance and luminance gradient maps in the MatLab code that was developed by Cai et al.<sup>31</sup>

*Step 5:* Import the HDR images into Evalglare to evaluate discomfort glare.

Evalglare is a tool used to evaluate existing glare measures and is used as a basis for the development of a new glare rating method, the daylight glare probability (DGP).



The results of the images are compared and correlated to the user assessment. The user assessment data is processed in a way that for each outcome there is a binary variable indicating if the subject is disturbed by glare or not in the scene. Evalglare is a tool that detects glare sources within a given image and calculates glare indices such as DGP, DGI, CGI, URG, and other important values which can also be used for other image evaluations. Evalglare uses images in the radiance image format which enables its user to evaluate simulated scenes.

Once the luminance maps are produced, the glare source must be identified. Three principal methods are tested for automatic detection of glare sources:

1. Calculating the average luminance of the entire image and counting every section as a glare source that is x-times higher than the average luminance.
2. Taking a fixed value and counting every section as a glare source that is higher than the fixed value.
3. Calculating the average luminance of a given zone (task area) and counting every section as a glare source that is x-times higher than the average luminance of the zone.

### **3.2 The Use of HDR Photography for Capturing Luminous Environments**

The equipment used in this study for the HDR photography includes a Canon EOS Rebel T2i fitted with a Sigma 4.5 mm F2.8 EX DC HSM circular fisheye lens, a heavy-duty tripod mounted to the camera, a Dell Latitude notebook computer for remote control of the camera and data recording, a Minolta luminance meter LS-100, a Minolta color meter CL-200A, and a reference X-Rite 18% grey checker for photometric calibrations. The camera Canon EOS Rebel T2i has 18 mega pixels (5184 x 3456 pixels),

18 shutter speeds (1/4000 seconds to 30 seconds), abundant fixable aperture sizes (f/1.4-f/32), and manual focus. Other types of cameras and lenses can also be used as well. The circular fisheye lens was selected for covering the entire front half hemisphere with 180-degree field of view and also for the benefit of discomfort glare calculation using the software Evalglare developed by Wienold <sup>42</sup>. Extensive research conducted in advance on calibrations of the camera and lens and the raw HDR images has largely facilitated the development of this camera-aided imaging method. <sup>4,51</sup> Predefined optimal settings of the camera and lens as listed on Table 3.2 were used in this study.

**Table 3.2:** Optimal Settings of the Camera and Lens Used in this Study <sup>31</sup>

Variables	Values
Camera	Canon EOS Rebel T2i
Lens	Sigma 4.5 mm F2.8 EX DC HSM circular fisheye lens
White balance	CCT, measured using the Minolta CL-200 A
ISO speed	100
Size/quality	Large/fine (JPEG) (5184 × 3456 pixels)
AF mode	One shot
AE lock button	AE lock
Metering mode	Partial
Colour space	sRGB
Exposure compensation	None
Auto-bracket	On
Drive mode	Continuous
Focal lengths of lens	4.5 mm
Aperture size	f/4.5
Shutter speeds	From 30 to 1/4000 s

### 3.3 The HDR Imaging Method and the Generation of HDR Images for Lighting

#### Analysis

The following is a description of the process involved in capturing HDR images of a luminous environment and the subsequent data processing. Several different case

studies took place. The case studies consisted of four different lighting scenarios. The scenarios include an electrically lit interior space, two daylight and electrically lit interior spaces, and an exterior lit space. Figure 3.2.1 shows the HDR equipment that was used for this study.



(a)



(b)



(c)



(d)



(e)



(f)

### **Figure 3.2.1: HDR Equipment**

(a) Canon EOS T2i camera (b) Sigma 10mm F2.8 fisheye lens (c) Illuminance and Luminance meter (d) Macbeth color checker (e) Dell computer for field measurements (f) Macbook pro for field measurements

#### *Camera Set-Up and Capturing LDR Images:*

An X-Rite 18% grey checker was placed across the scene in front of the camera. Before the photos were captured, a Chroma meter Minolta CL-200A was used to measure the correlated color temperature (CCT) and the vertical illuminance of light at the lens of the camera. The CCT is used for custom white balancing of the camera. The vertical illuminance was later used for glare calculations.

A Canon Rebel T2i with a Sigma 4.5mm F2.8 EX DC circular fisheye lens was mounted on a tripod at a location at each scene that represents the typical view of an occupant. The scene was photographed by capturing 18 low dynamic range (LDR) photographs using sequential exposures with an aperture size of f/4.5. The shutter speeds go from 30 seconds to 1/4000 seconds at the constant aperture. While the photos were being taken, simultaneous luminous measurements of the reference X-Rite 18% grey check was recorded using the Minolta LS-100 for photometric calibrations of the raw HDR images.

#### *LDR Images Fused to HDR Images:*

The LDR images of specific scenes were fused into a raw HDR image using a computer program called Photosphere. The LDR photographs with the lightest exposure were selected with the minimum RGB closest to and larger than 20. The darkest exposed

images selected must have a maximum RGB that is closest to and smaller than 200. <sup>4</sup>

Vignetting correction was used to account for the light drop-off in the periphery created by the Sigma circular fisheye lens. A photometric calibration was then conducted. The measured meter luminance ( $L_{\text{meter}}$ ) of the X-rite 18% grey checker was compared to the luminance extracted from the raw HDR images  $L_{\text{hdr}}$  to obtain a calibration factor. The calibration factor (CF) is the  $L_{\text{meter}}/L_{\text{hdr}}$ . The CF value that is specific for each test scene was used to calibrate the raw HDR images.

#### *Text File Using Radiance and Creating Luminance Maps:*

The images were then transformed into a text file in a software called Radiance. The luminance was extracted from the calibrated HDR images using every single pixel  $P_{\text{pix}} (X_{\text{pix}}, Z_{\text{pix}})$  using the command “pvalue” (`pvalue -o -h -b -$HDR . L_$HDR.txt`). The output text file of each calibrated HDR image was used to plot a two-dimensional luminance map, a two-dimensional gradient magnitude map, a luminance gradient magnitude map, and a 2D luminance gradient direction map.

The underlining coordinate of each map is plotted in pseudo color. The luminance gradient direction is measured anticlockwise in light of the x-axis of the photographic images (e.g. the angle 0 degree is the right hand, 90 degrees is up, 180 or -180 degrees is to the left, -90 degrees is down). The MatLab code developed for such image plotting is available online (<http://people.ku.edu/~h717c996/research.html>).

### **3.4 Use of HDR Images for Lighting Quality Assessment**

#### *2D Luminance and Luminance Gradient Maps:*

The 2D luminance and luminance gradient magnitude maps were further treated to identify potential glare sources. The luminance maps were filtered with the lower threshold value of  $500 \text{ cd/m}^2$  for electrically lit scenes and  $2000 \text{ cd/m}^2$  for daylight scenes. Threshold luminance gradient magnitude of  $500 \text{ cd/m}^2/\text{pixel}$  and  $2000 \text{ cd/m}^2/\text{pixel}$  were used for extreme light contrasts that are consistent with the threshold luminance values, whose polarity is shown by the gradient map.

The calibrated HDR images were then downsized to a pixel resolution of  $800 \times 800$  in the software program luminance HDR, and further treated in Evalglare for calculation of discomfort glare indices, including DGP, DGI, UGR, VCP, and CGI. The locations of those potential glare sources were also marked on the HDR images using color patches in Evalglare, which were then compared to the luminance and luminance gradient images plotted by MatLab. Such data treatments were all conducted on Max in X<sup>quartz</sup>.

Evalglare is a program that determines and evaluates glare sources within a 180 degree fish eye image given in the Radiance image format (.pic or .hdr). Due to performance reasons of the Evalglare code, the image should be smaller than  $800 \times 800$  pixels. The program calculates the daylight glare probability (DGP) as well as other glare indexes (dgi, ugr, vcp, cgi) to the standard output. The DGP describes the fraction of disturbed persons caused by glare from a daylight range from 0 to 1. Values that are lower than 0.2 are out of the range for user acceptance tests. The program is based on the studies done by J. Christoffersen and J. Wienold. The code can be used as follows:

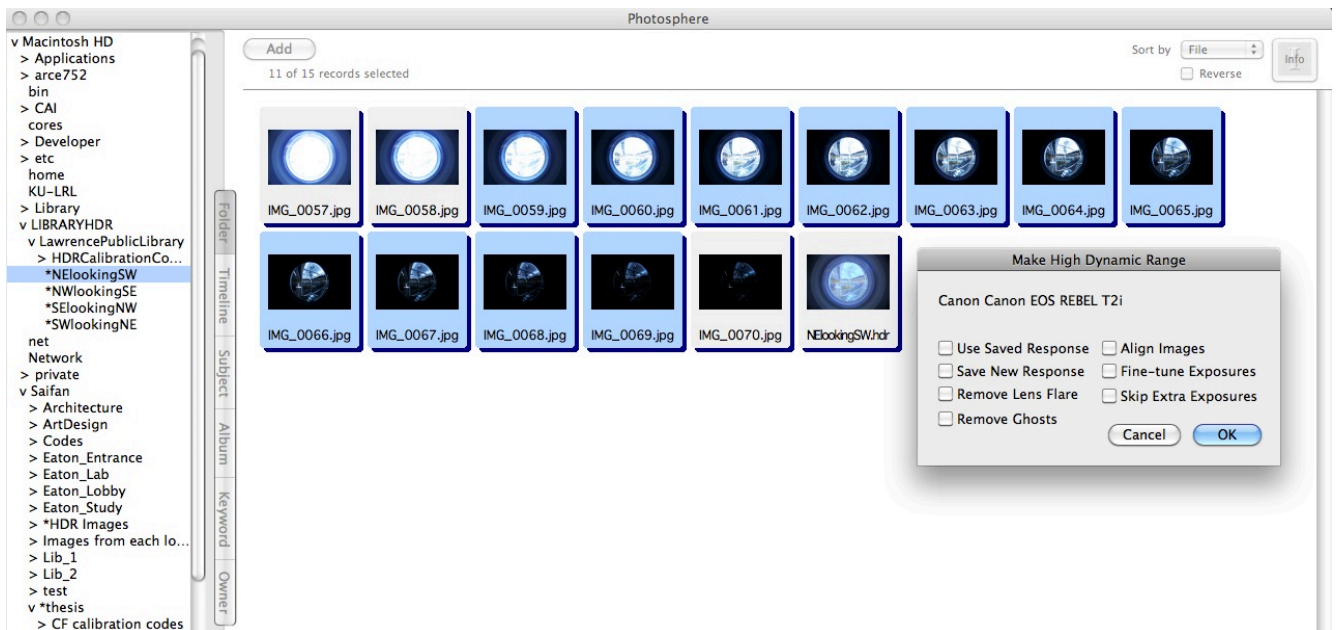
```
Evalglare [-s] [-y] [-Y value] [-a age] [-b factor] [-c checkfile] [-t xpos ypos angle] [-T
xpos ypos agle] [-d] [-r aple] [-i Ev] [-I Ev yfill_max y_fill_min] [-v] [-V] [-g type] [-G
type] [-vf viewfile] [-vtt] [-vv vertangle] [-vh horzangle] hdrfile
```

Below is another example of the code for glare calculations:

```
/usr/local/ray/evalglare -Y 500 -c arch_check.hdr -vta -vv 180 -vh 180
```

```
arch_crop_small.hdr
```

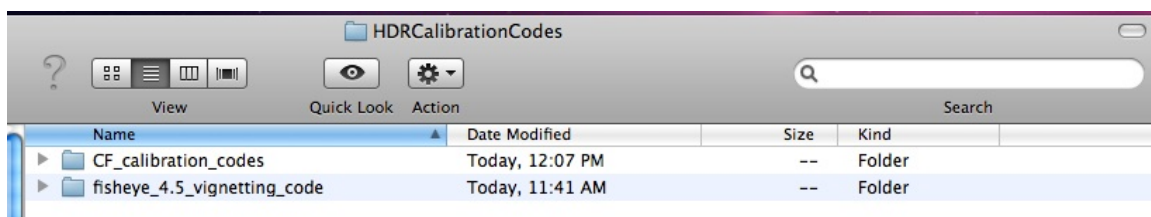
The following figures show screen shots of the steps to create an HDR image and the HDR luminance maps. Using a Canon Rebel T2i with a Sigma 4.5 mm F2.8 EX DC circular fisheye lens, mount the camera at a location in the scene that represents an occupant's typical view. Place the X-Rite grey checker in front of the camera at a location that can be seen. Using an HDR image fuser, set the camera to take 18 low dynamic range photographs with sequential exposures at an aperture size of f/4.5. While the photos are being taken, use the Minolta LS-100 to record the average calibrations of the HDR images. Once the images are loaded onto the computer, use the program called Photosphere to the images into a single HDR image.



**Figure 3.4.1:** Make an HDR Image Using Photosphere



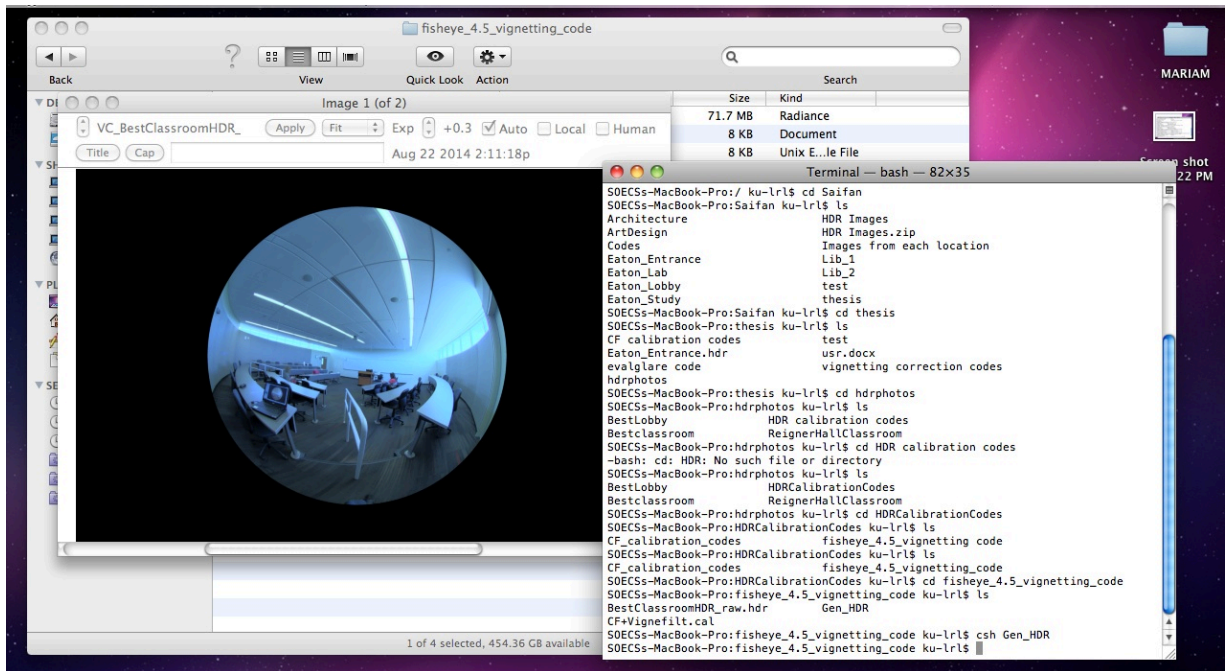
**Figure 3.4.2:** Sample RAW HDR Image Generated



**Figure 3.4.3:** HDR Calibration and Vignetting Codes



To calibrate an image, the RAW HDR image is transformed into a text file in a software called Radiance. Before that, the image is to be downsized to 800x800 pixels. The luminance was extracted from the calibrated HDR images using every single pixel  $P_{pix}(X_{pix}, Z_{pix})$  using the command “pvalue” (pvalue -o -h -b -\$HDR . L\_\$HDR.txt).



**Figure 3.4.4:** Terminal Language for HDR Calibration and Vignetting Codes

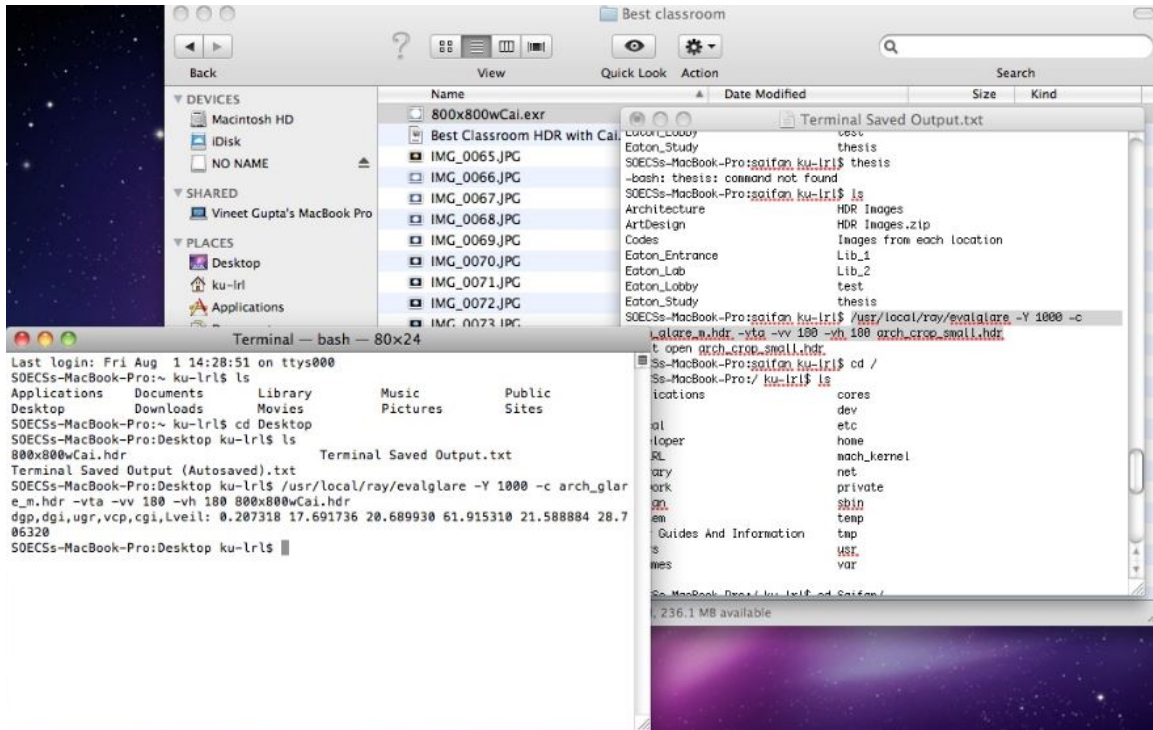
```

SOECSs-MacBook-Pro:/ku-lr$ cd Saifan
SOECSs-MacBook-Pro:Saifan ku-lr$ ls
Architecture          HDR Images
ArtDesign              HDR Images.zip
Codes                  Images from each location
Eaton_Entrance         Lib_1
Eaton_Lab              Lib_2
Eaton_Lobby            test
Eaton_Study            thesis
SOECSs-MacBook-Pro:Saifan ku-lr$ cd thesis
SOECSs-MacBook-Pro:thesis ku-lr$ ls
CF_calibration_codes   test
Eaton_Entrance_hdr     usr.docx
evalglare code         vignetting correction codes
hdrphotos
SOECSs-MacBook-Pro:thesis ku-lr$ cd hdrphotos
SOECSs-MacBook-Pro:hdrphotos ku-lr$ ls
BestLobby              HDR calibration codes
BestClassroom          ReignerHallClassroom
SOECSs-MacBook-Pro:hdrphotos ku-lr$ cd HDR calibration codes
-bash: cd: HDR: No such file or directory
SOECSs-MacBook-Pro:hdrphotos ku-lr$ ls
BestLobby              HDRCalibrationCodes
BestClassroom          ReignerHallClassroom
SOECSs-MacBook-Pro:hdrphotos ku-lr$ cd HDRCalibrationCodes
SOECSs-MacBook-Pro:HDRCalibrationCodes ku-lr$ ls
CF_calibration_codes    fisheye_4.5_vignetting code
SOECSs-MacBook-Pro:HDRCalibrationCodes ku-lr$ ls
CF_calibration_codes    fisheye_4.5_vignetting_code
SOECSs-MacBook-Pro:HDRCalibrationCodes ku-lr$ cd fisheye_4.5_vignetting_code
SOECSs-MacBook-Pro:fish-eye_4.5_vignetting_code ku-lr$ ls
BestClassroomHDR_raw.hdr  Gen_HDR
CF+Vignefilt.cal
SOECSs-MacBook-Pro:fish-eye_4.5_vignetting_code ku-lr$ csh Gen_HDR
SOECSs-MacBook-Pro:fish-eye_4.5_vignetting_code ku-lr$ cd .
SOECSs-MacBook-Pro:fish-eye_4.5_vignetting_code ku-lr$ ls
BestClassroomHDR_raw.hdr  Gen_HDR
CF+Vignefilt.cal          VC_BestClassroomHDR_raw.hdr
SOECSs-MacBook-Pro:fish-eye_4.5_vignetting_code ku-lr$ ls
BestClassroomHDR_raw.hdr  Gen_HDR
CF+Vignefilt.cal          VC_BestClassroomHDR_raw.hdr
SOECSs-MacBook-Pro:fish-eye_4.5_vignetting_code ku-lr$ cd ..
SOECSs-MacBook-Pro:HDRCalibrationCodes ku-lr$ ls
CF_calibration_codes      fisheye_4.5_vignetting_code
SOECSs-MacBook-Pro:HDRCalibrationCodes ku-lr$ cd CF_calibration_codes/
SOECSs-MacBook-Pro:CF_calibration_codes ku-lr$ ls
CF+Vignefilt.cal          VC_BestClassroomHDR_raw.hdr
Gen_HDR

```

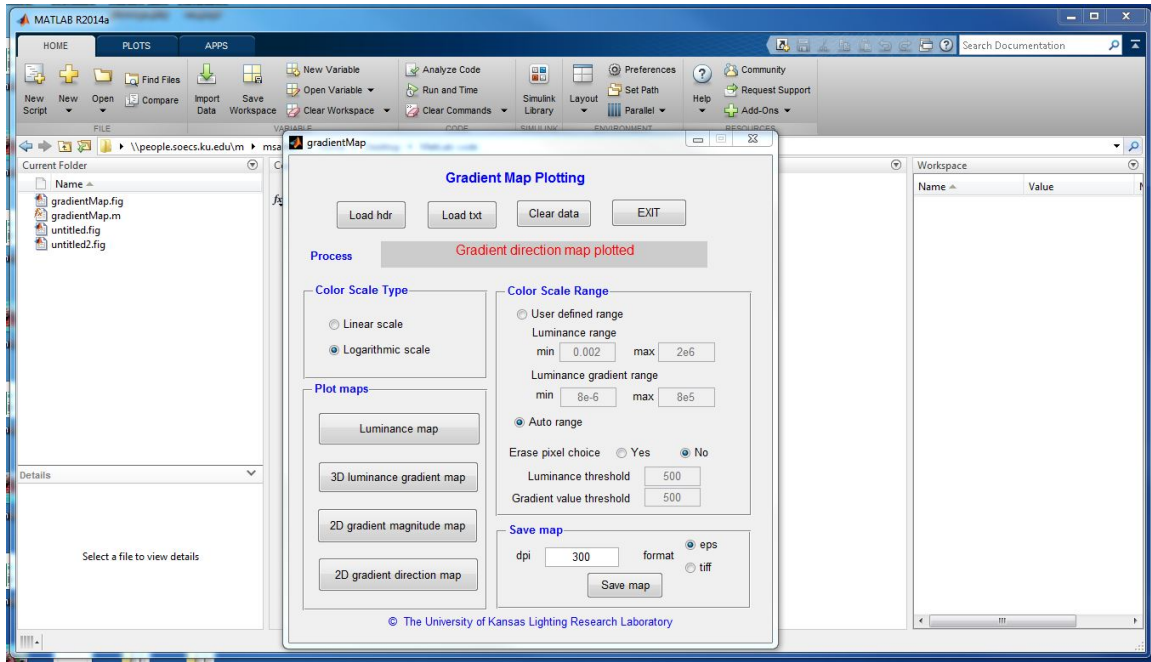
**Figure 3.4.5: Terminal Language Sample**

This figure is an example of the code used for a glare calculation. Locate the text file of the RAW HDR image and type in the following code. “Arch\_check.hdr” is the future file name of the image to be exported. “Arch\_crop\_small.hdr” is the name of the text file located in the folder in the terminal language. /usr/local/ray/evalglare -Y 500 -c arch\_check.hdr -vta -vv 180 -vh 180 arch\_crop\_small.hdr.



**Figure 3.4.6:** Terminal Language for HDR Image Output

Once the previous code is input into the text file, the HDR image is generated and placed in the folder where it was originally located. The text file outputs text that represents the DGP (daylighting glare probability), DGI (daylighting glare index), UGR (Unified Glare Rating), VCP (visual comfort probability), and more.



**Figure 3.4.7: MatLab Gradient Map Plotting**

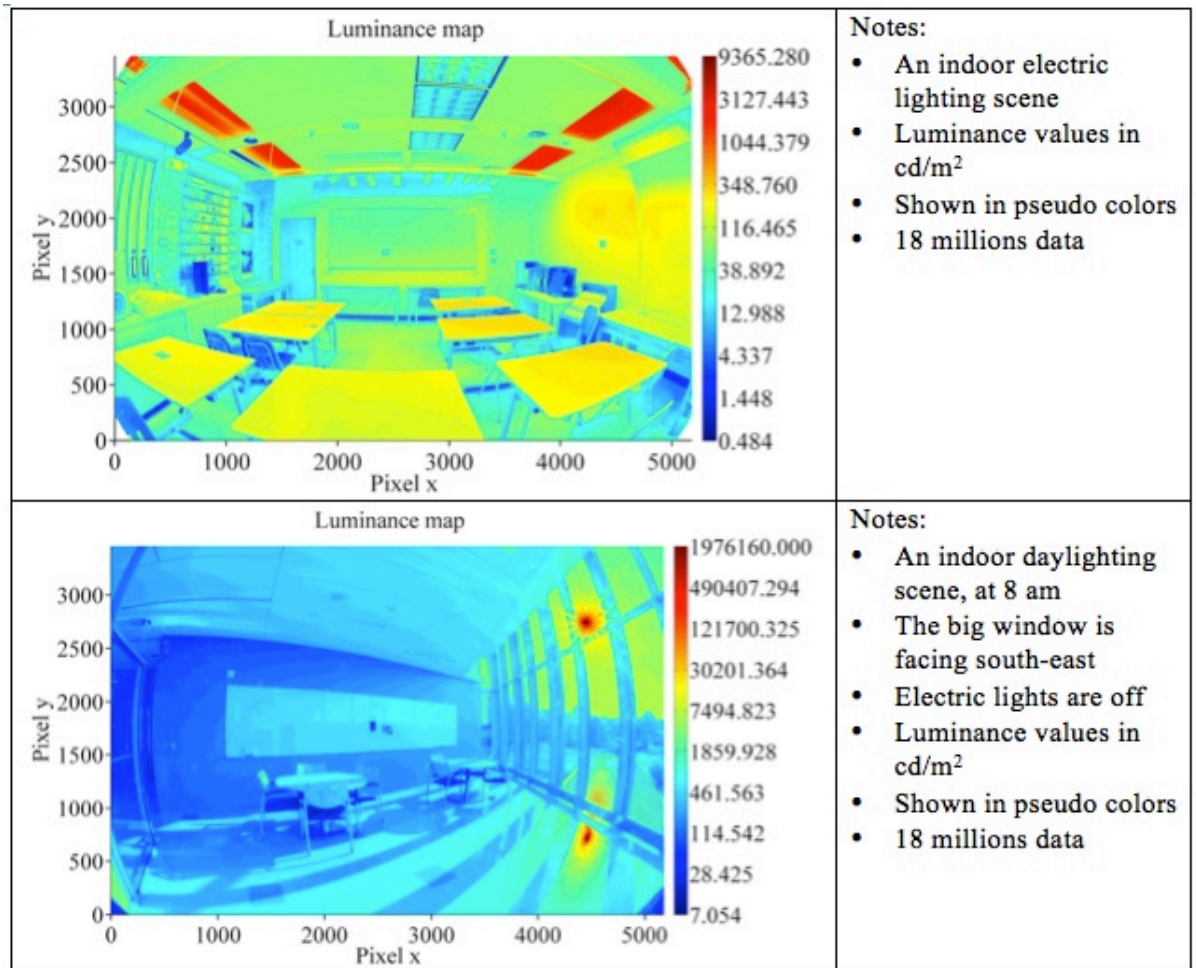
From the previous steps, the luminance was extracted from the calibrated HDR images using every single pixel  $P_{pix} (X_{pix}, Z_{pix})$  using the command “pvalue” ( $p_{value} -o -h -b -\$HDR . L\_ \$HDR.txt$ ). The output text file of each calibrated HDR image is used to plot a two-dimensional luminance map, a two-dimensional gradient magnitude map, a luminance gradient magnitude map, and a 2D luminance gradient direction map. Using MatLab software, load the text file of the HDR image, input the logarithmic scale and plot the maps as indicated previously.

### **3.5 Questionnaire for the Efficiency of the Camera-Aided Design Method and Analysis**

A questionnaire was formed which shows six graphs that contain luminance maps, gradient maps, or gradient direction maps. The images for the questionnaire are shown as follows in Figure 3.5.1 (a)-(f). With each map, the same four yes-or-no questions were asked as follows:

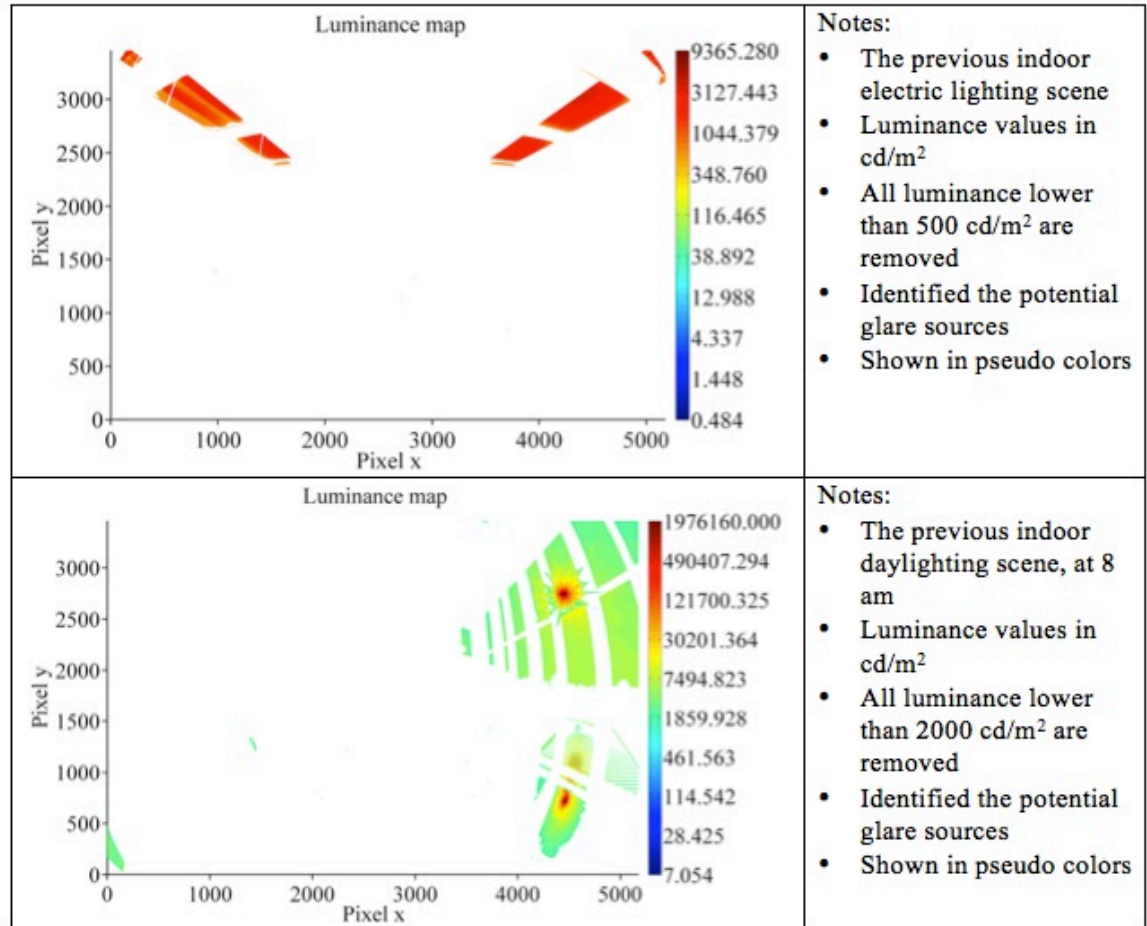
- Are these HDR images useful for post-occupancy evaluation or retrofit?
- Do these HDR images provide more information than the bare eyes can handle?
- If the images above are computer-generated scenes of projects still in design, will they help in lighting design?
- Would you be interested in using these HDR images for lighting practice?

This questionnaire was sent out to 40 professionals who have beginning to high-level experience in the lighting design field. The feedback was processed through an online survey and then analyzed in percentage of how many designers answered yes-or-no for each question as shown in Figure 3.5.2.

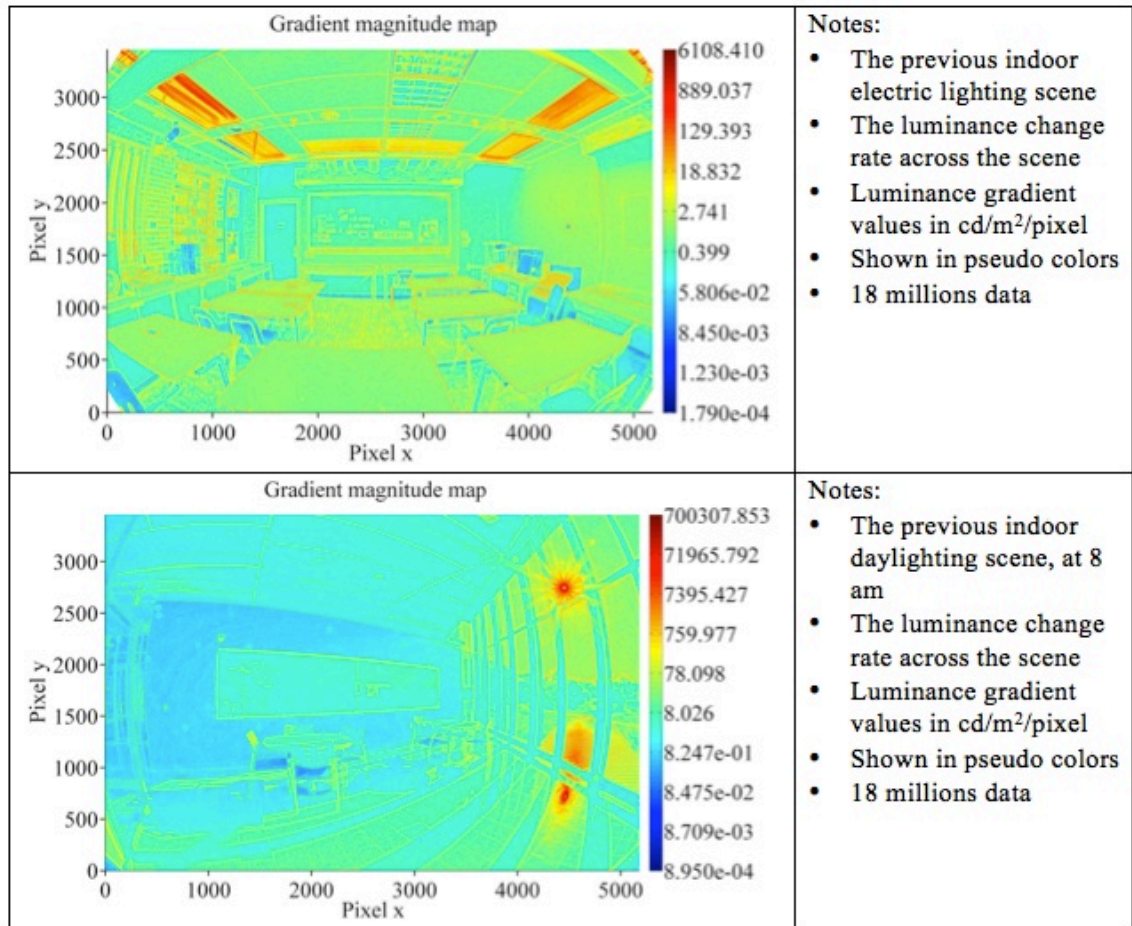


(a) Question 1. Luminance Map. Indoor electric scene luminance map of two classrooms with daylight and electric light.





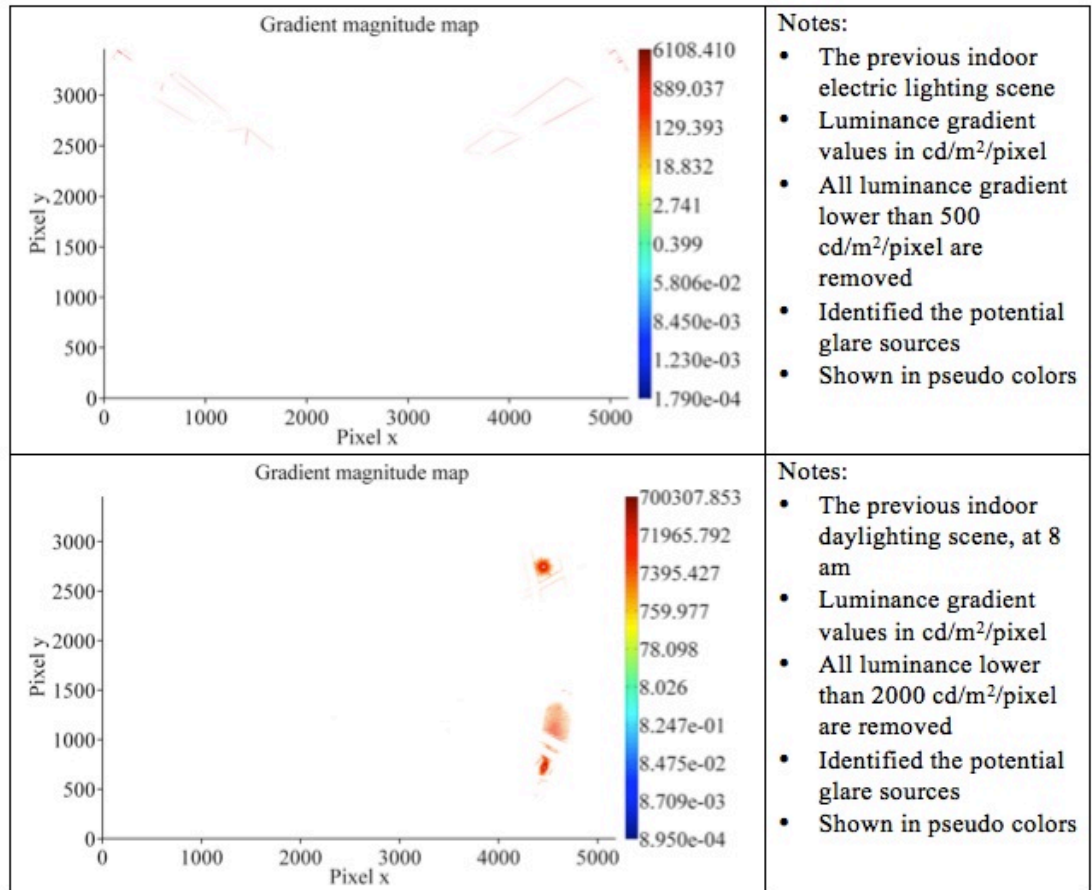
(b) Question 2. Luminance Map Filtered with a Lower Threshold Value. Indoor electric scene luminance map of two classrooms with daylight and electric light with a threshold luminance lower than  $500 \text{ cd/m}^2$  and  $2000 \text{ cd/m}^2$ .



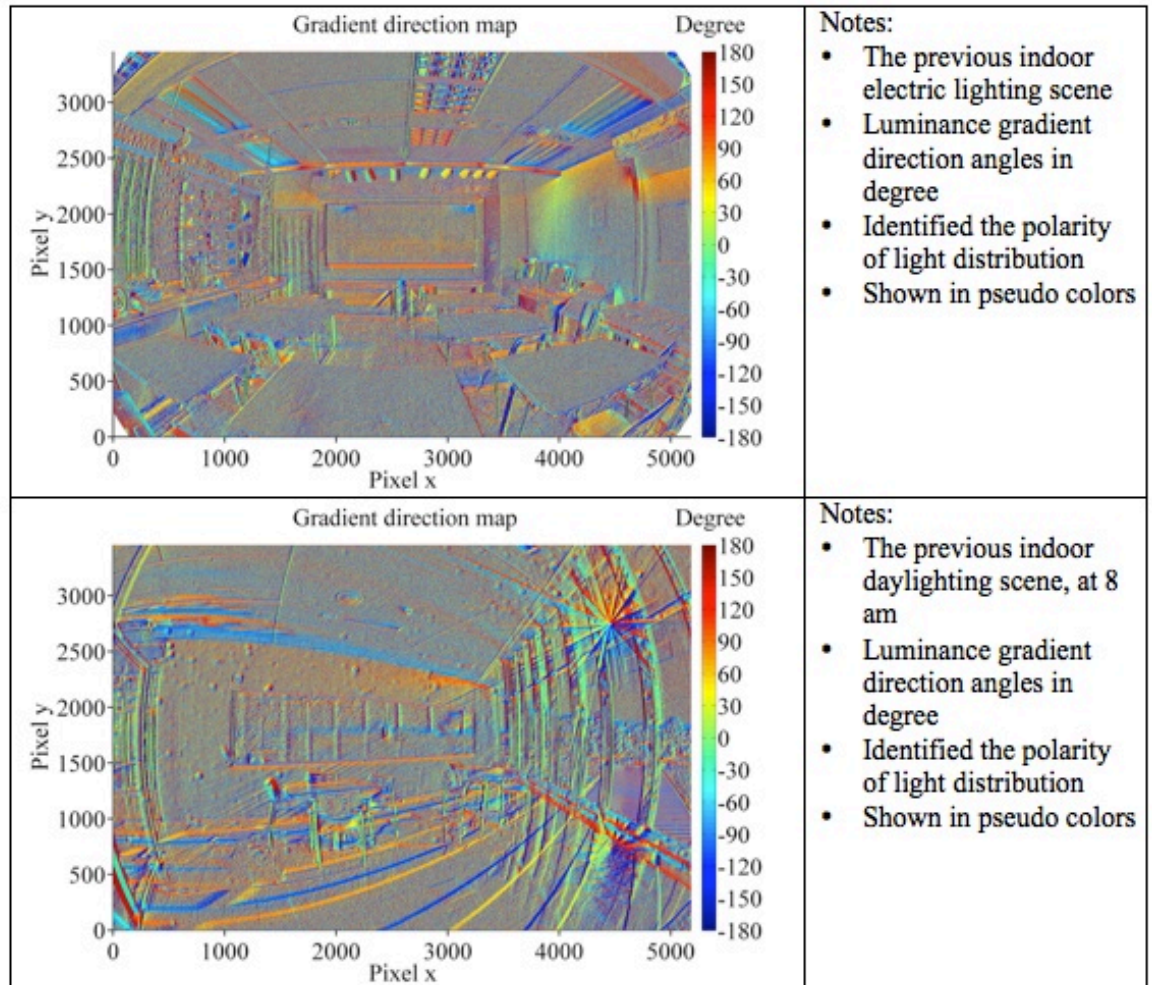
(c) Question 3. Luminance Gradient Magnitude Map. Indoor electric scene

luminance gradient map of two classrooms with daylight and electric light.

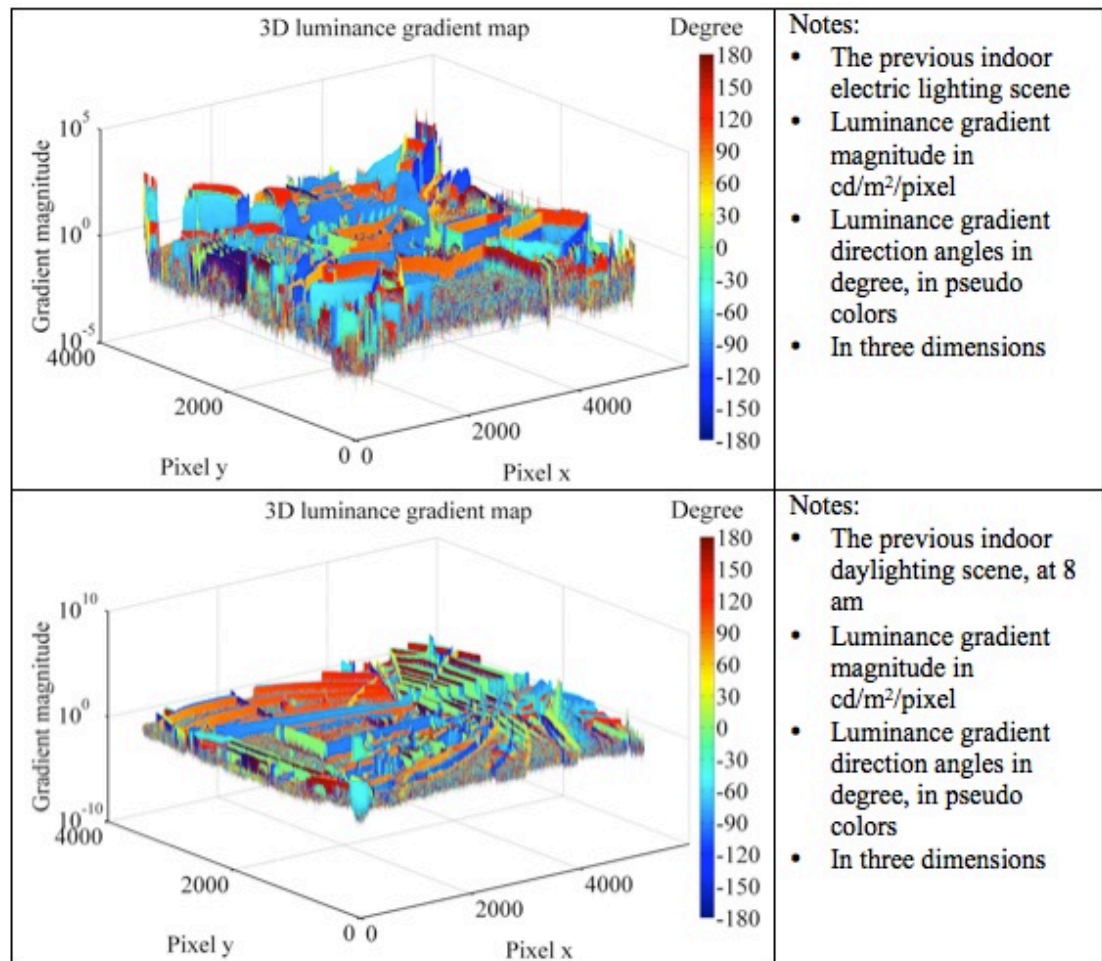




(d) Question 4. Luminance Gradient Magnitude Map Filtered with Lower Threshold Value. Indoor electric scene gradient magnitude map of two classrooms with daylight and electric light.



(e) Question 5. Luminance Gradient Direction Map. Indoor electric scene gradient direction map of two classrooms with daylight and electric light.

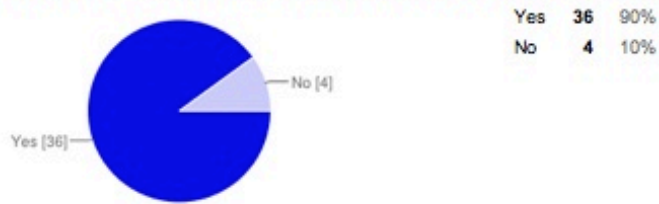


(f) Question 6. 3D Luminance Gradient Map. Indoor electric scene 3D luminance gradient map of two classrooms with daylight and electric light.

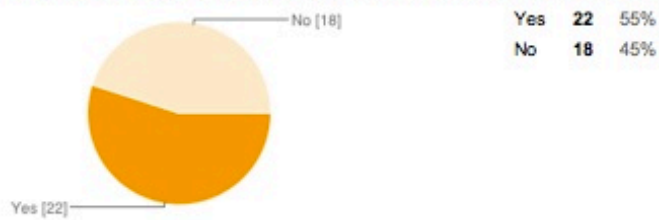
**Figure 3.5.1** HDR Images for Questionnaire

**Figure 1. Luminance Map**

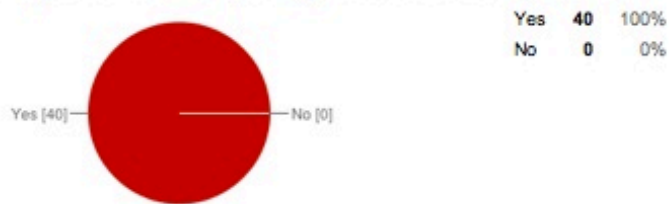
**Are these HDR images useful for post-occupancy evaluation or retrofit?**



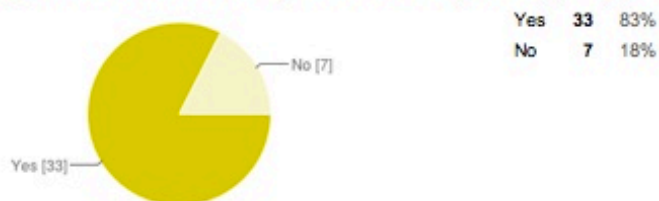
**Do these HDR images provide more information than bare eyes can handle?**



**If the images above are computer generated scenes of projects still in design, will they help in lighting design?**



**Would you be interested in using these HDR images for lighting practice?**



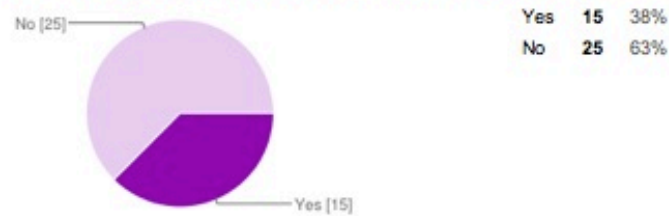
(a)

**Figure 2. Luminance Map Filtered with a Lower Threshold Value**

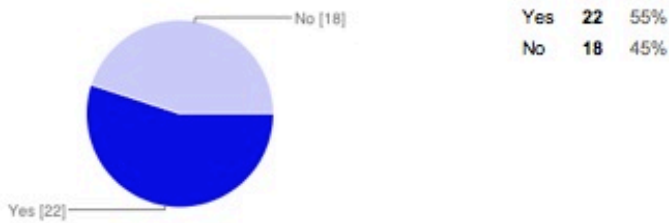
**Are these HDR images useful for post-occupancy evaluation or retrofit?**



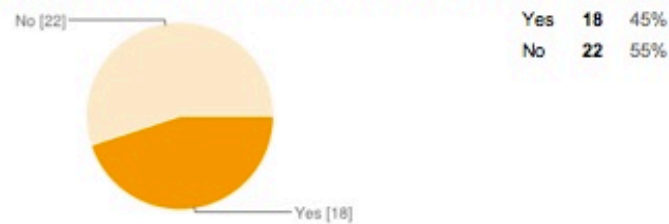
**Do these HDR images provide more information than bare eyes can handle?**



**If the images above are computer generated scenes of projects still in design, will they help in lighting design?**



**Would you be interested in using these HDR images for lighting practice?**

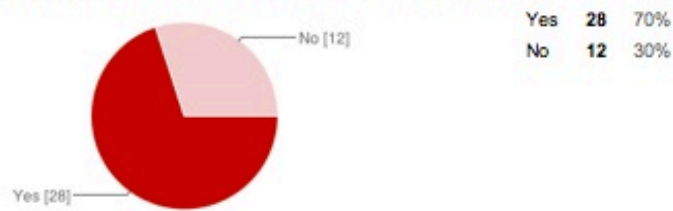


(b)

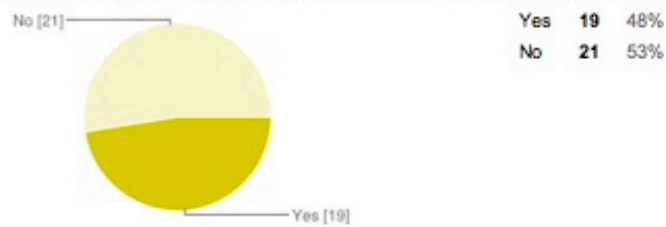


**Figure 3. Luminance Gradient Magnitude Map**

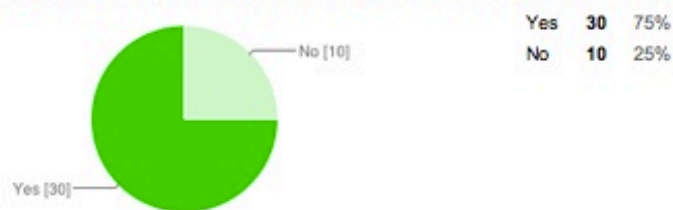
**Are these HDR images useful for post-occupancy evaluation or retrofit?**



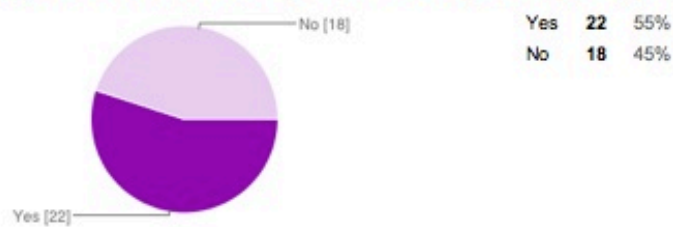
**Do these HDR images provide more information than bare eyes can handle?**



**If the images above are computer generated scenes of projects still in design, will they help in lighting design?**



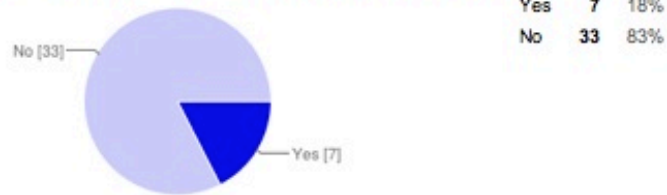
**Would you be interested in using these HDR images for lighting practice?**



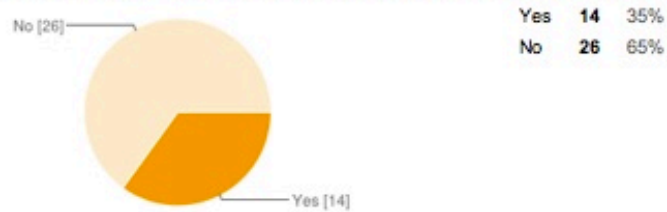
(c)

**Figure 4. Luminance Gradient Magnitude Map Filtered with Lower Threshold Value**

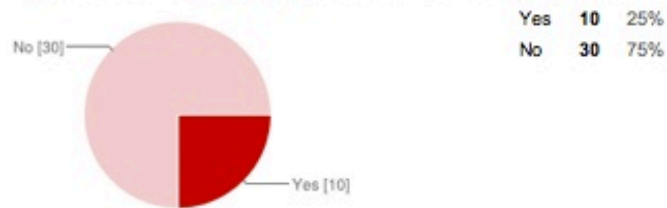
**Are these HDR images useful for post-occupancy evaluation or retrofit?**



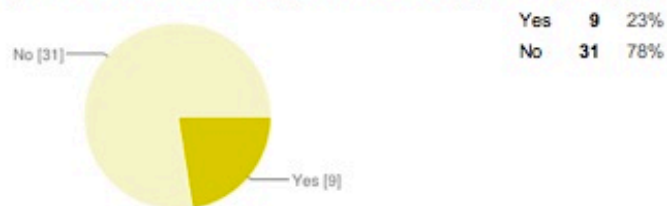
**Do these HDR images provide more information than bare eyes can handle?**



**If the images above are computer generated scenes of projects still in design, will they help in lighting design?**



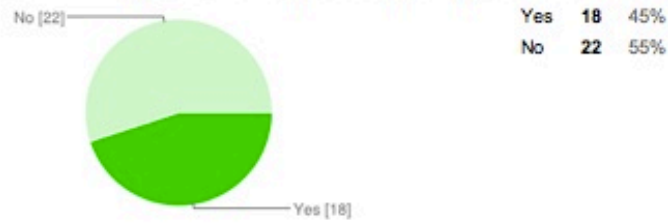
**Would you be interested in using these HDR images for lighting practice?**



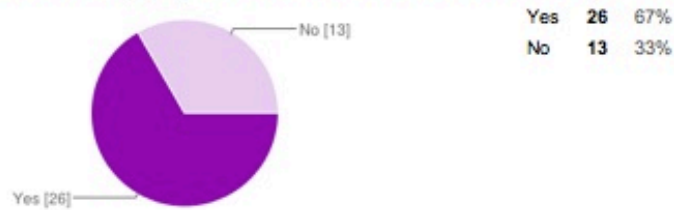
(d)

**Figure 5. Luminance Gradient Direction Map**

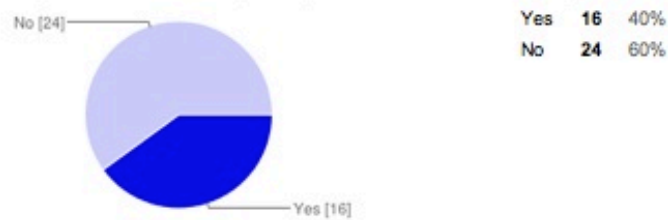
**Are these HDR images useful for post-occupancy evaluation or retrofit?**



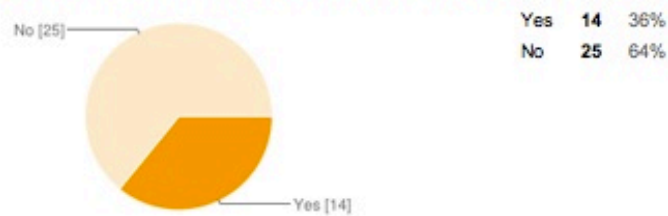
**Do these HDR images provide more information than bare eyes can handle?**



**If the images above are computer generated scenes of projects still in design, will they help in lighting design?**



**Would you be interested in using these HDR images for lighting practice?**



(e)



**Figure 6. 3D Luminance Gradient Map**

**Are these HDR images useful for post-occupancy evaluation or retrofit?**



Response	Count	Percentage
Yes	11	28%
No	29	73%

**Do these HDR images provide more information than bare eyes can handle?**



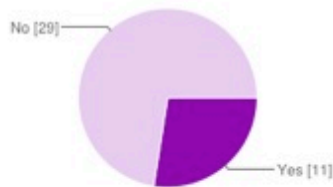
Response	Count	Percentage
Yes	27	68%
No	13	33%

**If the images above are computer generated scenes of projects still in design, will they help in lighting design?**



Response	Count	Percentage
Yes	12	30%
No	28	70%

**Would you be interested in using these HDR images for lighting practice?**



Response	Count	Percentage
Yes	11	28%
No	29	73%

(f)

**Figure 3.5.2 Survey Feedback for HDR Questionnaire**

Six figures were shown on the questionnaire and this figure shows the different answers from lighting designers as a percentage. The figures show four different questions that were asked for the different figures shown in the questionnaire.

The questionnaire shows that when the designers looked at the *luminance map*, 90% of them thought that the HDR images were useful, 55% thought that the images had more information than the bare eyes could handle, 100% agreed that the images would help in lighting design, and 83% were interested in using the HDR images for lighting practice. When the designers looked at the *luminance map filtered with a lower threshold value*, 50% thought that the HDR images were useful, and 38% thought that the images had more information than the bare eyes could handle. When the designers looked at the *luminance gradient magnitude map*, 70% thought that the HDR images were useful, and 75% thought that the images would help in lighting design. When looking at the *luminance gradient magnitude map filtered with a lower threshold value*, 83% of designers thought that the images were not useful, 75% thought that it would not help in lighting design, and 78% were not interested in using that HDR image. When looking at the *luminance gradient direction map*, 67% thought that the images had more information than the bare eyes could handle, and 64% were not interested in using the HDR image. When looking at the *3D luminance gradient map*, 72% thought that the HDR images were not useful, 70% thought that the images would not help in lighting design, and 73% were not interested in using the HDR image.

The questionnaire results show that most designers thought the luminance map and the luminance gradient magnitude map were easy to understand and that the designers would be interested in using it in aiding their design practice. However, the results show that most designers do not understand the luminance gradient magnitude map filtered with lower threshold value, the luminance gradient direction map, and the 3D luminance gradient map.

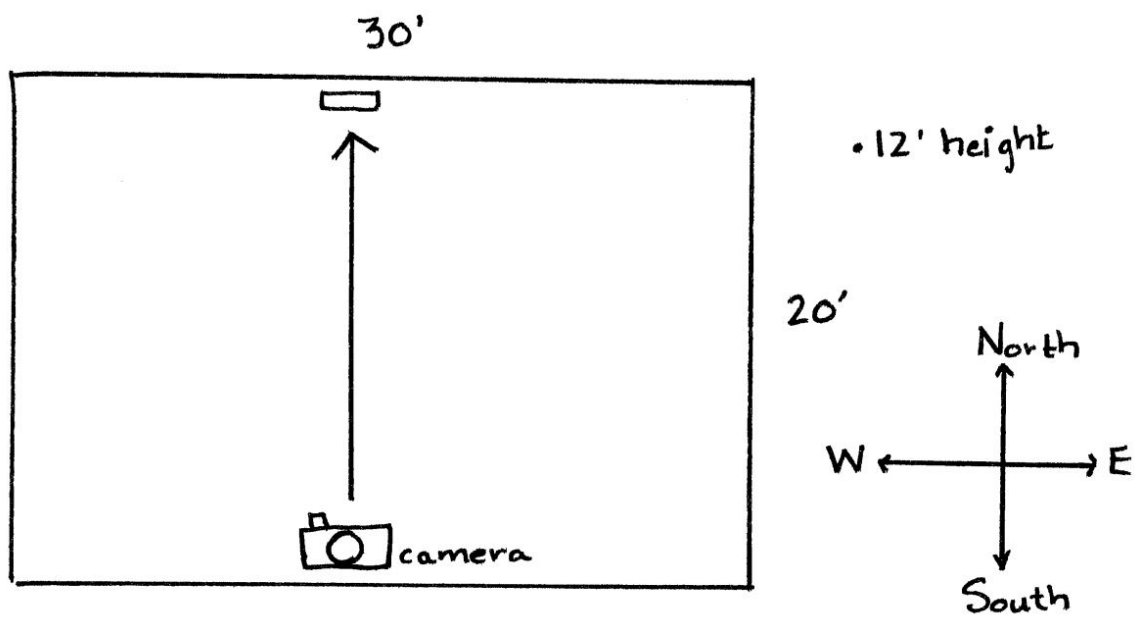
## CHAPTER 4: CASE STUDIES

### 4.1 Case Studies: Electrically Lit Interior Space

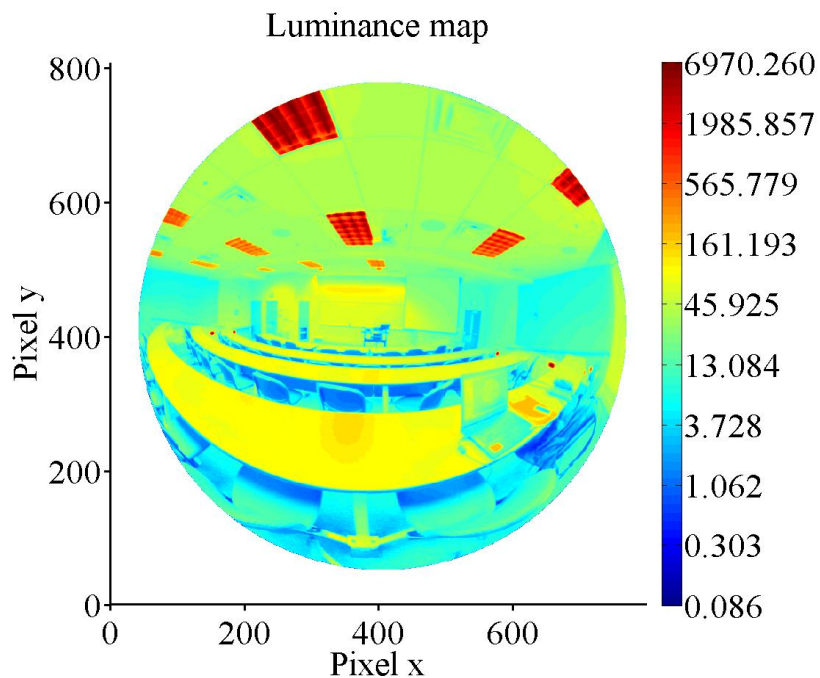
A classroom in Regnier Hall at the University of Kansas Edwards campus is shown. The measurement was conducted on June 14<sup>th</sup> at 11 AM without daylight. The camera was mounted in the back of the classroom at 1.4m above the ground and aimed at the white board. The X-Rite Macbeth color checker was vertically mounted on the white board area near the front of the classroom for the photometric calibration. The average measured values were 3055 Kelvin and 566 lux. The electric lighting included 2x4 foot (.61x1.2m) troffers with T8 lamps.



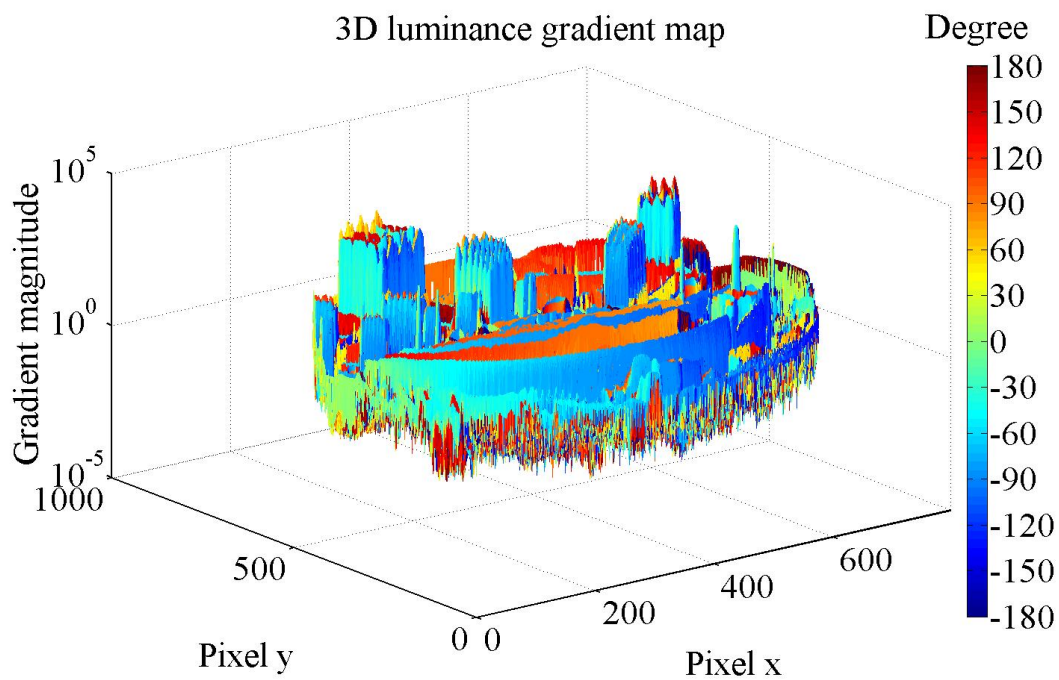
**Figure 4.1.1:** Regnier Hall at the University of Kansas



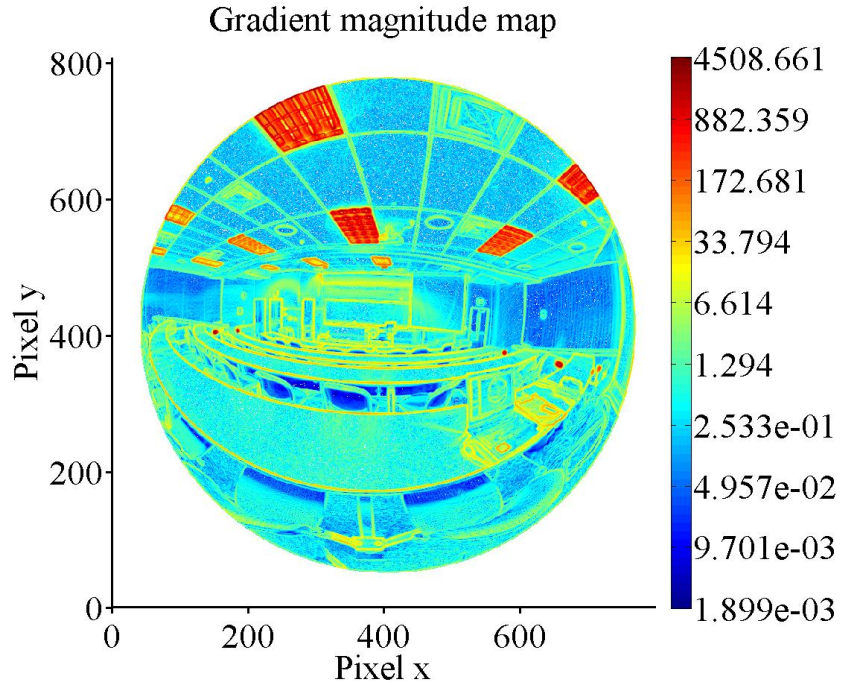
**Figure 4.1.2:** Regnier Hall Camera Location (9.1m x 6.1m with 3.6m height)



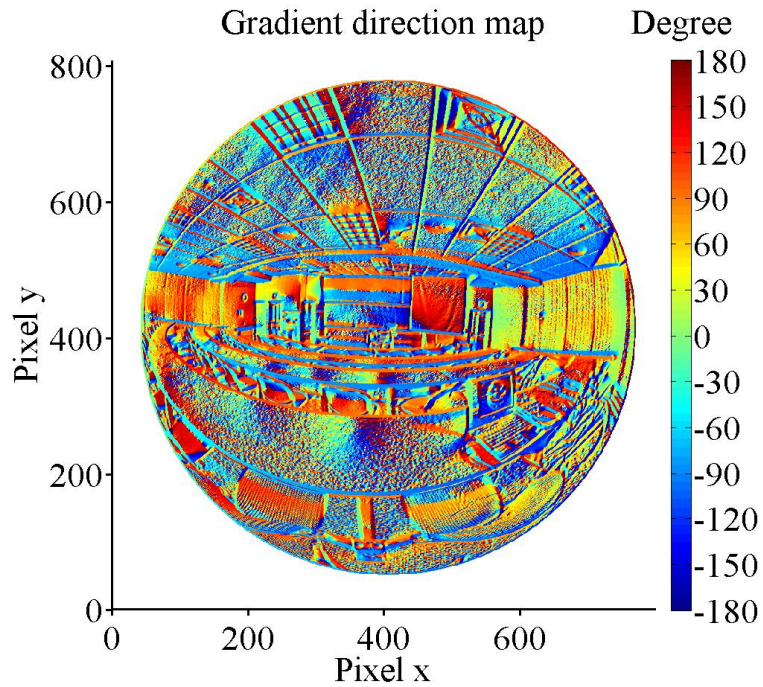
(a) *Luminance Map* [A map that shows the luminance values in  $\text{cd/m}^2$ .]



(b) *3D Luminance Gradient Map* [A map that shows the luminance gradient in degrees.]



(c) 2D Gradient Magnitude Map [A map that shows the gradients of luminance.]



(d) 2D Gradient Direction Map [A gradient direction map that shows which direction the light is going in degrees.]



*(e) The potential glare sources marked on the HDR image by Evalglare [The colors on the picture show where there may be a potential for glare.]*

**Figure 4.1.3** Electrically Lit Interior Space (a) – (e) shows the spatial distribution of the luminance and luminance gradient values across the classroom located in Regnier Hall. It was found that the classroom had a generally even lighting distribution. The tables in the classroom had a threshold value of around  $160 \text{ cd/m}^2$ , which may cause a lot of glare for the users in the classroom. The white board at the front of the classroom also shows a threshold value of around  $160 \text{ cd/m}^2$ , which may be a potential lighting hazard that may be bothersome to users. The most light came from the electric lighting in the room with about  $6970 \text{ cd/m}^2/\text{pixel}$ . The  $\text{DGP} = 0.16$ ,  $\text{DGI} = 13.29$ ,  $\text{UGR} = 15.56$ ,  $\text{VCP} = 84.94$ ,  $\text{CGI} = 17.05$ , and  $L_{\text{veil}} = 13.07$ . The DGP value shows that there was no glare in the classroom



and that it had a value of less than 0.35 which means it was imperceptible. Also, the DGI is less than 14 so it is also imperceptible, which means there is potentially no glare.

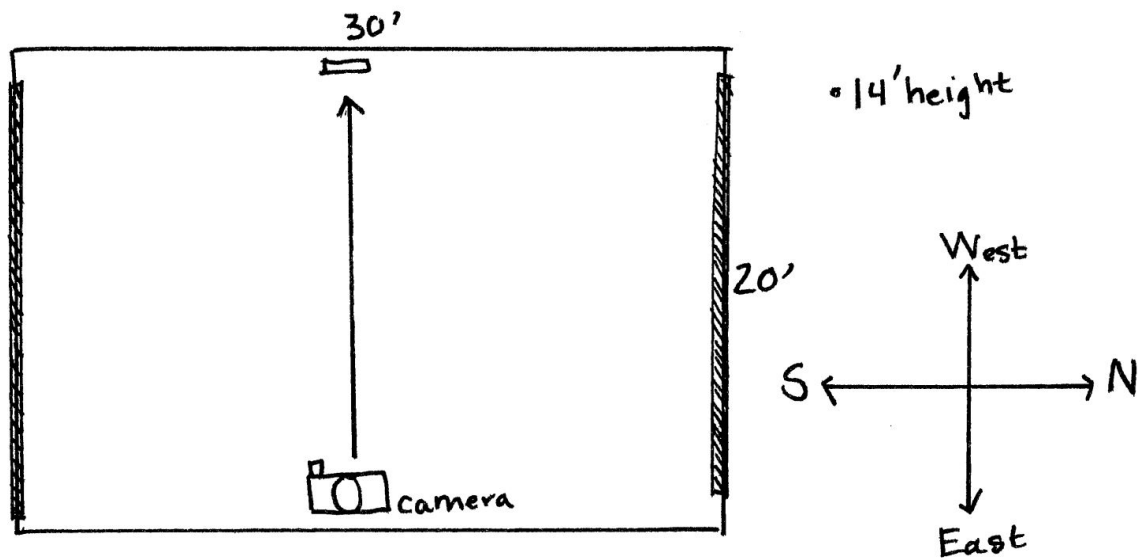
#### **4.2 Case Studies: Daylit and Electrically Lit Interior Space (Part 1)**

A classroom in Business Engineering Science and Technology building at the University of Kansas Edwards campus is shown. The measurement was conducted on June 14<sup>th</sup> at 10:30AM with daylight and electric light. The camera was mounted in the back of the classroom at 1.4m above the ground and aimed at the white board. The location of the camera was in the back right corner of the classroom. The X-Rite Macbeth color checker was vertically mounted on the first table to the left near the front of the classroom for the photometric calibration. The average measured values were 4000 Kelvin and 437 lux. The electric lighting included 3 rows of linear LED lights. The classroom had linear windows on the both sides as shown.

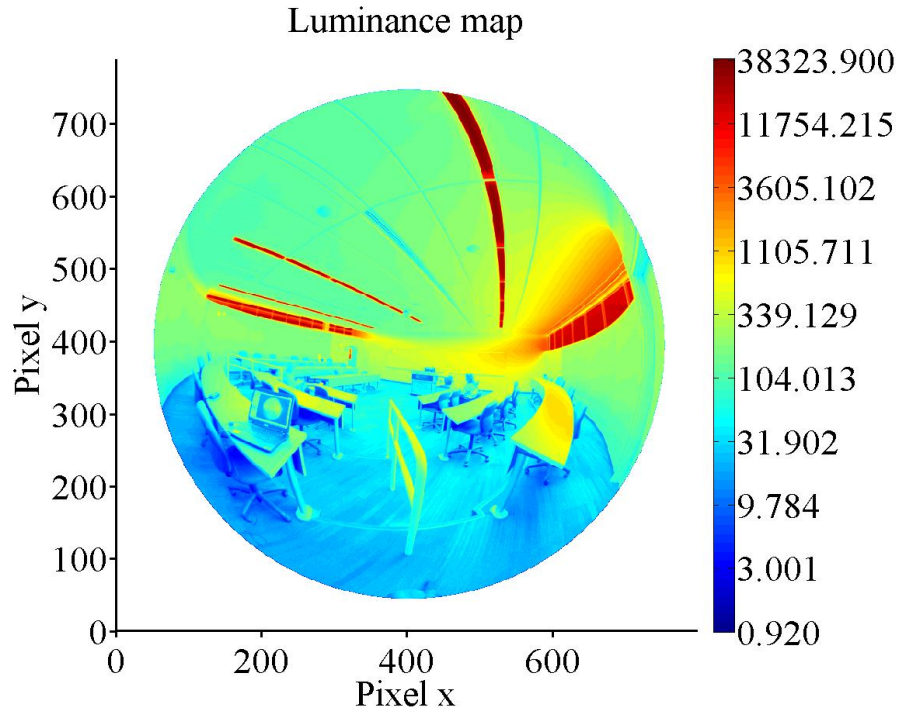


**Figure 4.2.1: BEST Classroom**

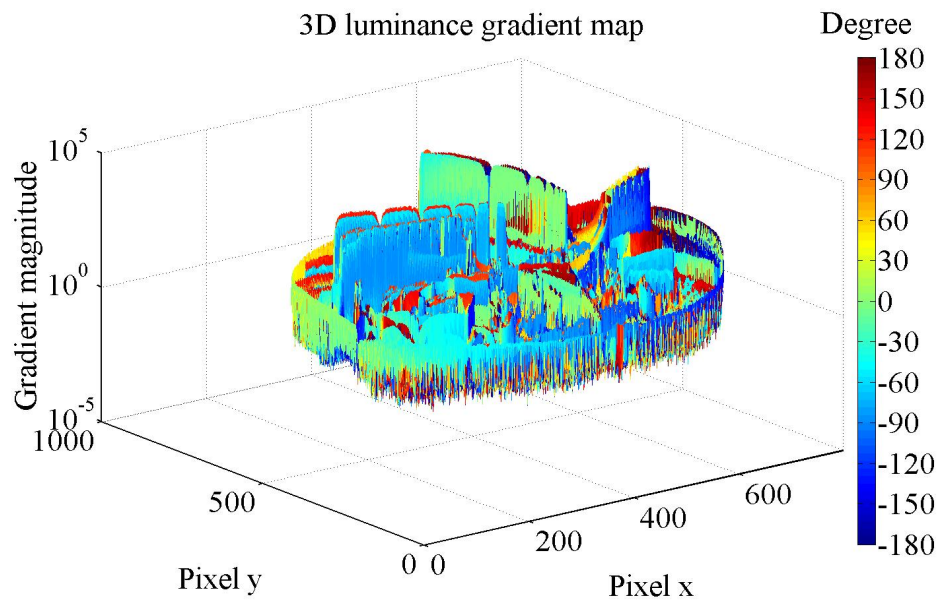




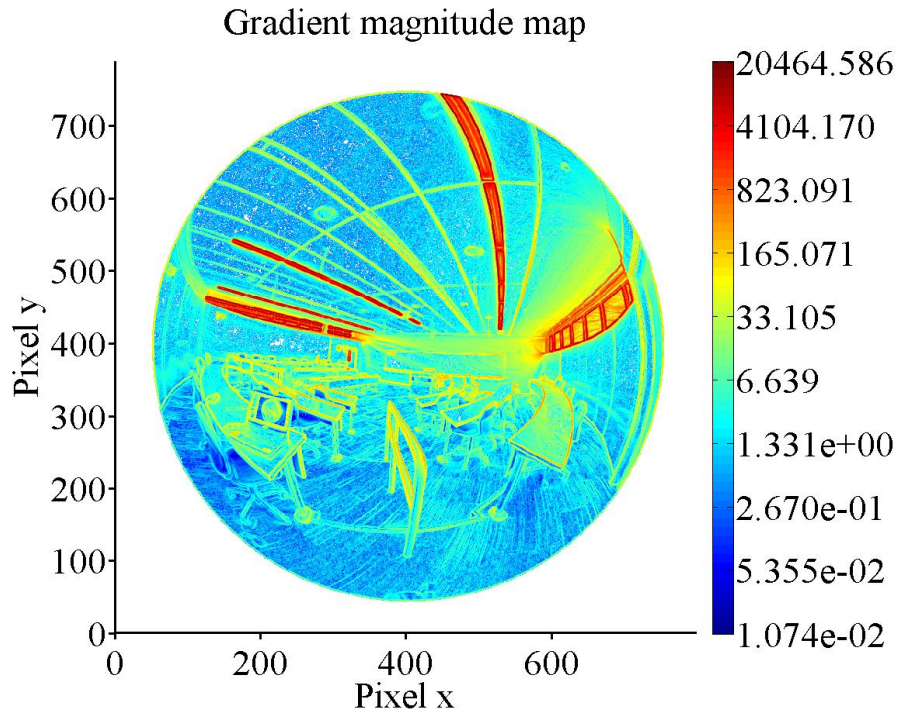
**Figure 4.2.2:** BEST Classroom Camera Location (9.1m x 6.1m with 4.2m height)



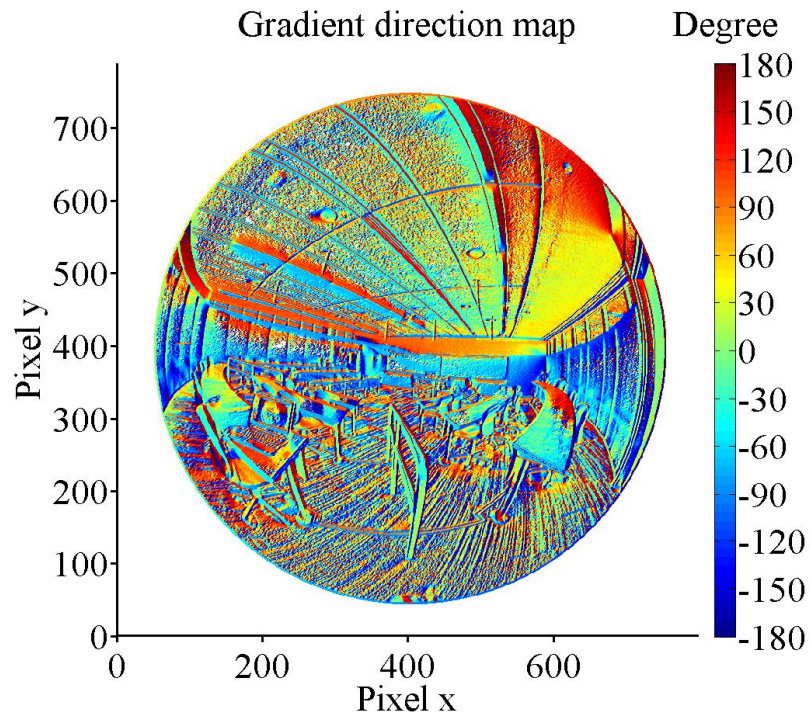
(a) *Luminance Map* [A map that shows the luminance values in  $\text{cd/m}^2$ .]



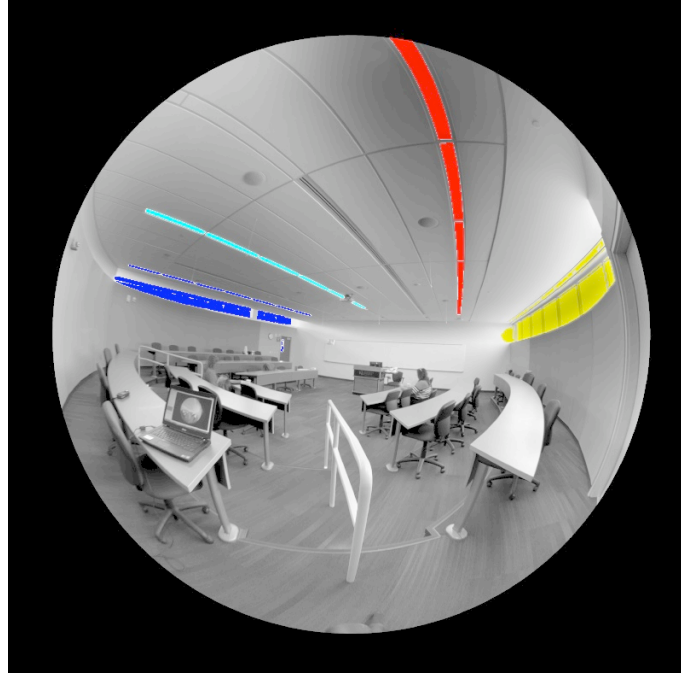
(b) *3D Luminance Gradient Map* [A map that shows the luminance gradient in degrees.]



(c) 2D Gradient Magnitude Map [A map that shows the gradients of luminance.]



(d) 2D Gradient Direction Map [A gradient direction map that shows which direction the light is going in degrees.]



*(e) The potential glare sources marked on the HDR image by Evalglare [The colors on the picture show where there may be a potential for glare.]*

**Figure 4.2.3** Daylit and Electrically Lit Interior Space (a) – (e) shows the spatial distribution of the luminance and luminance gradient values across the classroom located in Regnier Hall. It was found that the classroom was mostly lit by the daylighting that came in on one side of the classroom. The lighting that came through the windows had the highest threshold values of around  $38000 \text{ cd/m}^2/\text{pixel}$ . The desks at one side of the classrooms at the time that the photo was taken may have potential lighting hazards. The tables and the white board reflect light with a threshold value of around  $1100 \text{ cd/m}^2/\text{pixel}$ .

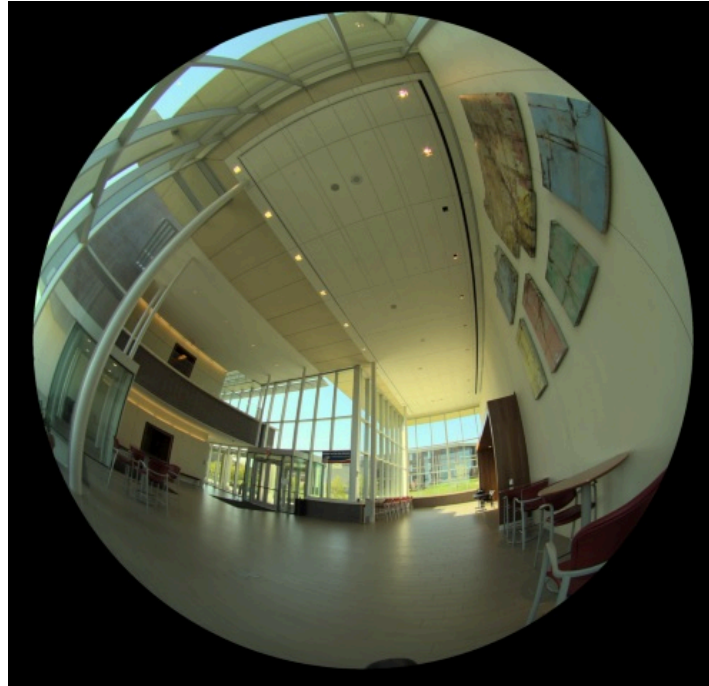
The daylighting in this classroom might cause potential discomfort glare whereas the glare from the electric lighting is negligible. The  $DGP = 0.31$ ,  $DGI = 22.52$ ,  $UGR = 27.03$ ,  $VCP = 11.22$ ,  $CGI = 30.82$ , and  $L_{\text{veil}} = 154.75$ . The DGP is less than 14 which means that the glare in the classroom is imperceptible and it is a comfortably lit classroom. The DGI

shows that the room is “just comfortable” according to Table 2.1 Scales of Discomfort.

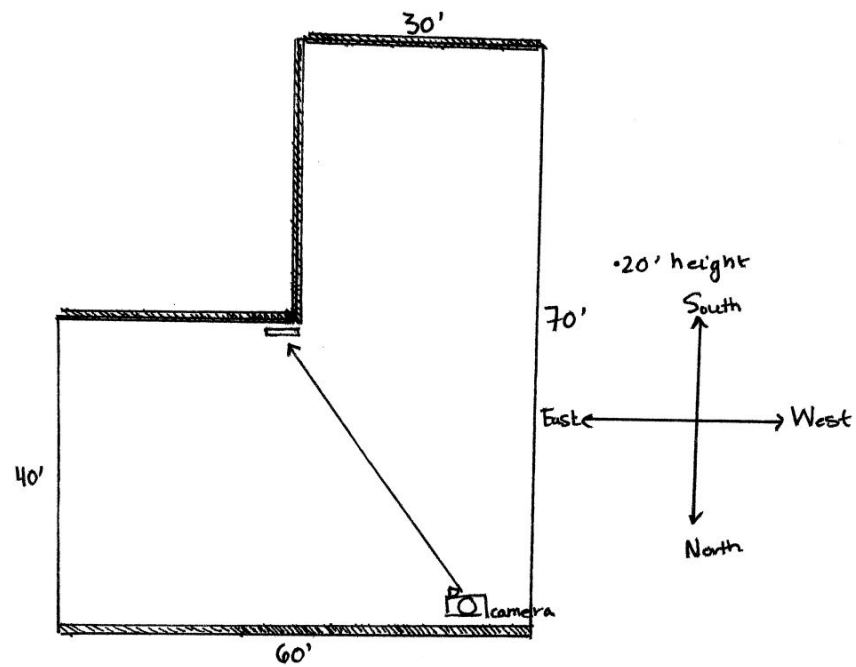
The VCP shows that the scale of discomfort for the light fixture would be intolerable.

#### **4.2 Case Studies: Daylit and Electrically Lit Interior Space (Part 2)**

The lobby in the Business Engineering Science and Technology building at the University of Kansas Edwards campus is shown. The measurement was conducted on June 14<sup>th</sup> at 10AM with daylight and electric light. The camera was mounted in a corner of the lobby at 1.4m above the ground and aimed at the south windows. The X-Rite Macbeth color checker was vertically mounted on the south facing windows for the photometric calibration. The average measured values were 5940 Kelvin and 1506 lux. The electric lighting included 10 small aperture can lights in the ceiling. The lobby was surrounded by floor to ceiling windows on the north and south façades.

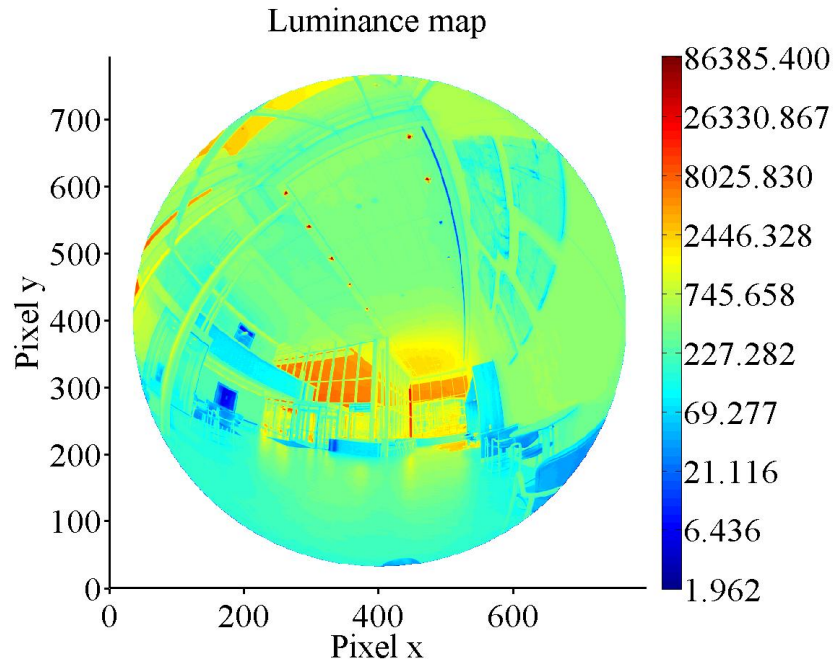


**Figure 4.2.4: BEST Lobby**

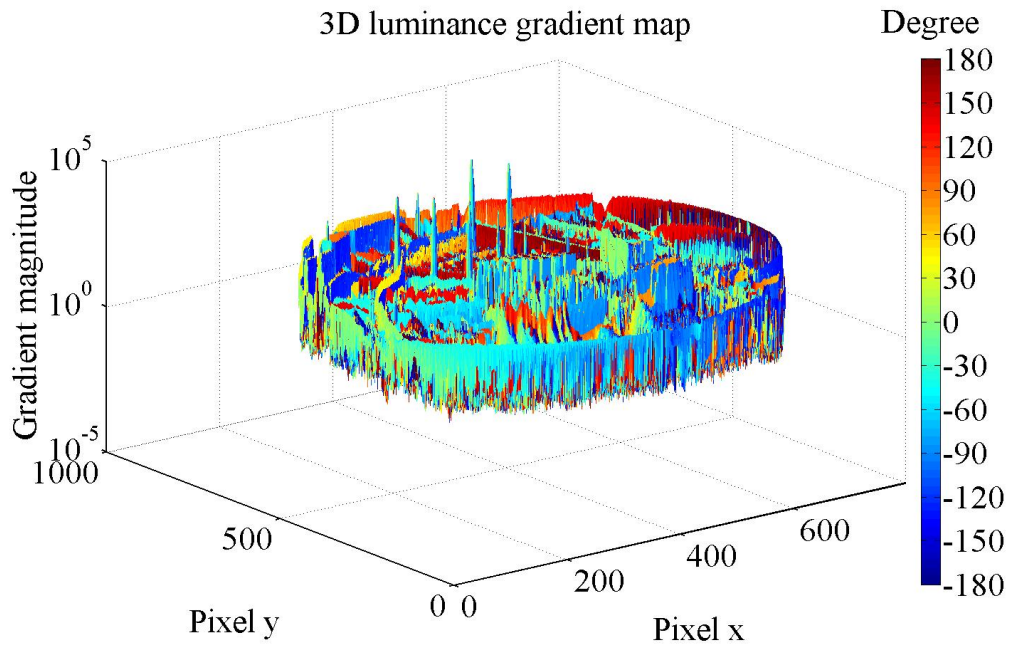


**Figure 4.2.5: BEST Lobby Camera Location (9.1m x 21.4m x 18m x 12m with 6m height)**

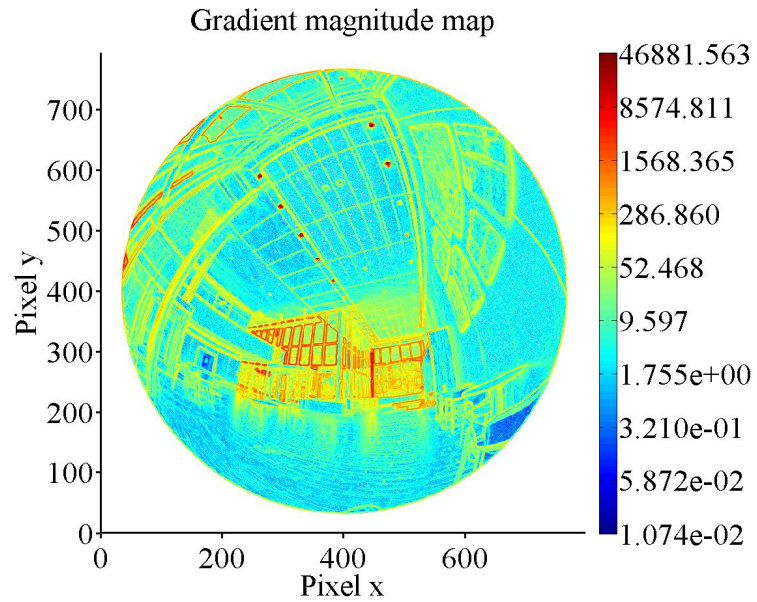




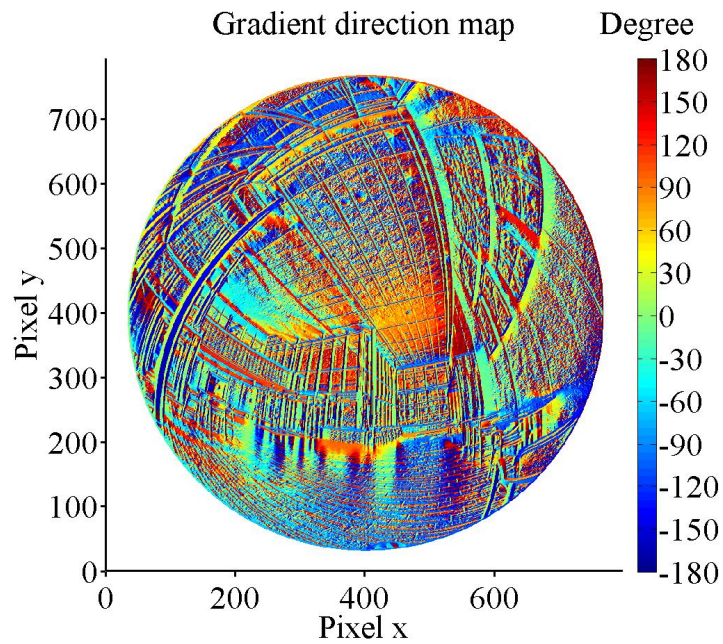
(a) *Luminance Map* [A map that shows the luminance values in  $\text{cd/m}^2$ .]



(b) *3D Luminance Gradient Map* [A map that shows the luminance gradient in degrees.]

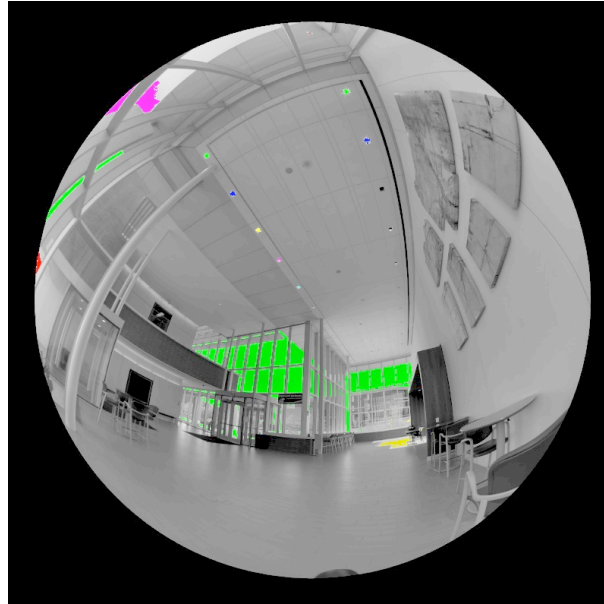


(c) 2D Gradient Magnitude Map [A map that shows the gradients of luminance.]



(d) 2D Gradient Direction Map [A gradient direction map that shows which direction the light is going in degrees.]





*(e) The potential glare sources marked on the HDR image by Evalglare [The colors on the picture show where there may be a potential for glare.]*

**Figure 4.2.6** Daylit & Electrically Lit Interior Space (a) – (e) shows the spatial distribution of the luminance and luminance gradient values across the lobby. It was found that the lobby area was lit mostly by the natural light coming through the floor-to-ceiling windows from the south façade at that moment. The natural light coming into the lobby could potentially cause hazardous glare on the ground as shown with a threshold value of about  $2446 \text{ cd/m}^2/\text{pixel}$ . The ceiling near the south façade windows are also showing potential for hazardous glare. Otherwise, there is a fairly even illumination at the center of the lobby with about  $69 \text{ cd/m}^2/\text{pixel}$ . The  $\text{DGP} = 0.31$ ,  $\text{DGI} = 20.28$ ,  $\text{UGR} = 24.63$ ,  $\text{VCP} = 26.66$ ,  $\text{CGI} = 29.31$ , and  $\text{L}_{\text{veil}} = 145.11$ . According to the scales of discomfort, the daylighting glare probability would be imperceptible. Therefore, at that time of the day, there was no glare from the daylight. The DGI was just acceptable for the

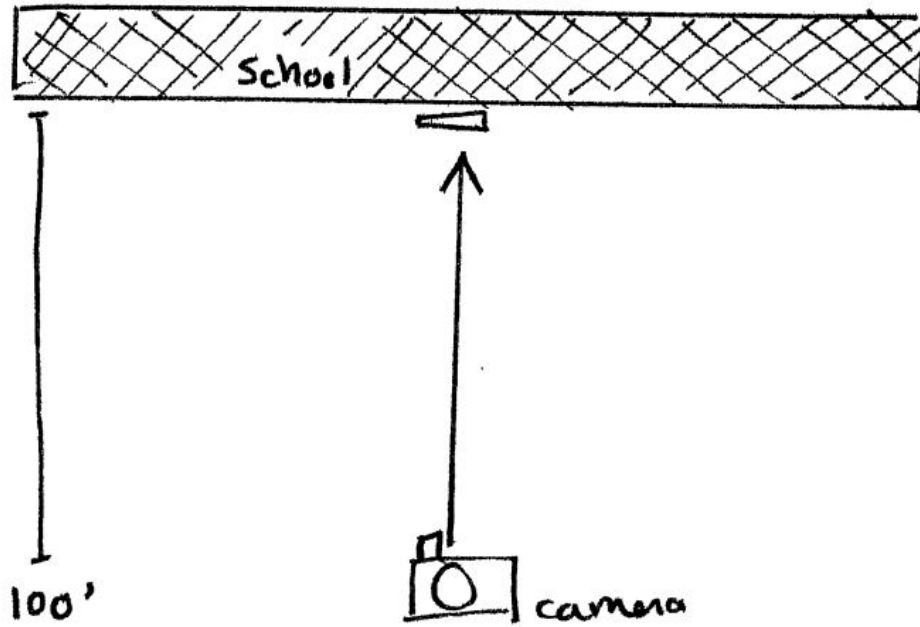
scale of discomfort and the unified glare rating (UGR) shows that the space is  
“unacceptable.”

### **4.3 Case Studies: Exterior Lighting**

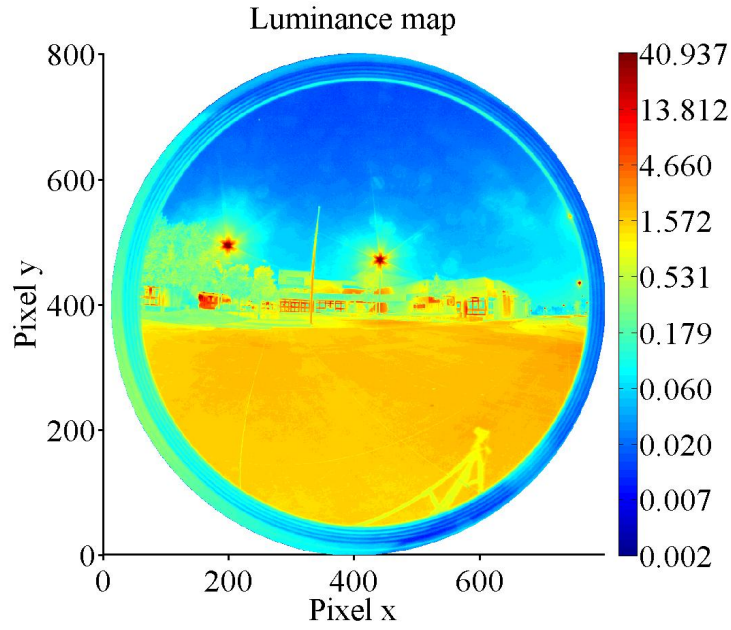
The exterior of a Blue Valley High School in Overland Park is shown. The measurement was conducted on October 18<sup>th</sup> at 8PM. The camera was mounted in a walking area at 1.4m above the ground and façade of the high school. The location of the camera was not recorded due to the lack of reference points in the world coordinate system. The X-Rite Macbeth color checker was vertically mounted on the ground for the photometric calibration. The average measured values were 4415 Kelvin and 7.6 lux. This photo was taken at night so there is no daylighting. The electric lighting consists of street pole lighting and building lighting.



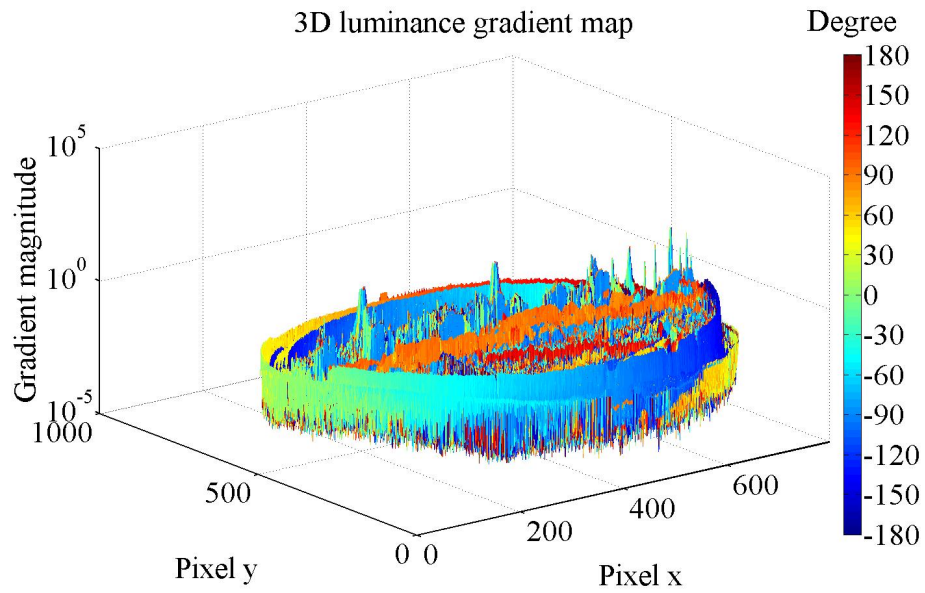
**Figure 4.3.1:** Blue Valley High School at Night



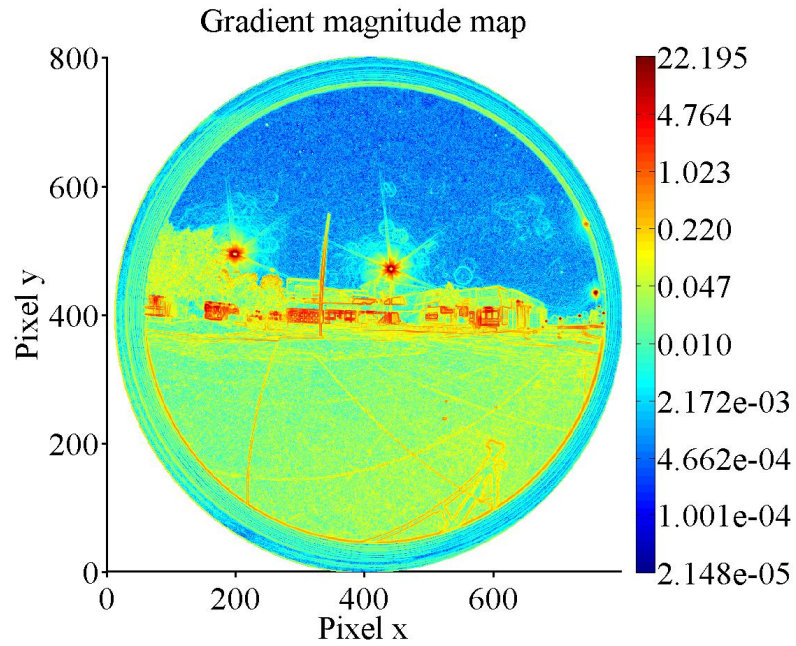
**Figure 4.3.2:** Blue Valley High School at Night Camera Location (30m distance)



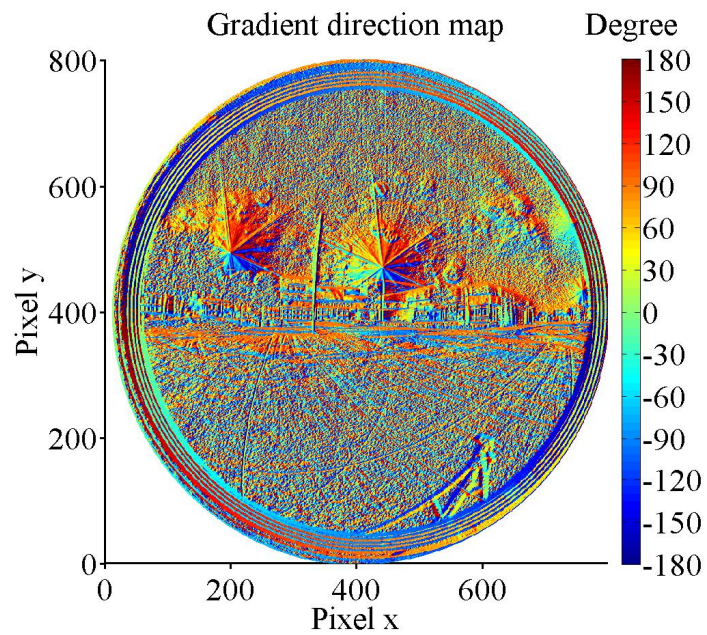
(a) *Luminance Map* [A map that shows the luminance values in  $\text{cd/m}^2$ .]



(b) *3D Luminance Gradient Map* [A map that shows the luminance gradient in degrees.]



(c)2D Gradient Magnitude Map [A map that shows the gradients of luminance.]



(d)2D Gradient Direction Map [A gradient direction map that shows which direction the light is going in degrees.]



*(e) The potential glare sources marked on the HDR image by Evalglare [The colors on the picture show where there may be a potential for glare.]*

**Figure 4.3.3** Exterior Lighting (a) – (e) shows the spatial distribution of the luminance and luminance gradient values across the classroom located at the Blue Valley High School. It was found that the exterior of the building has very low lighting threshold. The outdoor luminance distribution at night was at a low level except for the floodlights and one area of the façade which may cause discomfort glare. The logo of the school is not shown because there is not a light fixture aimed at the logo. The polarity of the luminance gradient had dominant colors on the floodlights. The  $DGP = 0.0031$ ,  $DGI = -3.19$ ,  $UGR = -6.11$ ,  $VCP = 100$ ,  $CGI = -3.08$ , and  $L_{veil} = 0.0396$ . The data points measure show that glare in the exterior space are imperceptible. That means that there is no glare in the outside area of the high school. The high school would need more lighting to emphasize the façade and for safety.

## **CHAPTER 5: CONCLUSION AND DISCUSSION**

### **5.1 Conclusions**

This paper has introduced the deployment of high dynamic range (HDR) photography as an imaging method to evaluate lighting in an existing interior and exterior space. It details the procedure and how the HDR images can be used for interpreting the lighting quality of different luminous environments. The method considers the human visual perception that lighting designers should take into account to create a pleasant and high quality luminous environment. In addition, this paper has introduced the measurement equipment, procedure, and follow up data treatments that use software programs such as Radiance, Photosphere, Luminance HDR, and a MatLab code available online free to use for plotting HDR images. (<http://people.ku.edu/~h717c996/research.html>).

A total of four case studies were conducted in this study that include an electrically lit interior space, two electrically lit interior spaces with daylight, and an exterior lit space. The qualities of the luminous environments were judged based on the HDR images and luminous maps produced.

The first case study considered an electrically lit interior space. A classroom in Regnier Hall at the University of Kansas campus was photographed. The room had no windows and only had several fluorescent fixtures recessed into the ceiling. The luminance map shows that most of the potentially glare might come from the fluorescent fixtures. The scales of discomfort show that there is no glare and that it is imperceptible. Looking at the gradient direction map, one can see that the projector screen is reflecting



light back 180 degrees to the users in the classroom. This might be a potential area of glare. To improve this space, a designer could use a fixture that has direct and indirect light for a more even illumination in the classroom. The designer could also change the color of the desks so they are not so reflective to help reduce glare to the desks.

The second case study looked at a classroom at the Business Engineering Science and Technology building at the University of Kansas. This classroom has both electrical linear LED light fixtures and daylight coming into the space. When a designer looks at the luminance map, they can see that most of the potential light hazards come from the electrical light fixtures. There also seems to be more light reflected off of the desks closest to the windows and on the walls in front of the classroom. The values indicate that the glare is almost imperceptible, however, the electric lighting in this classroom is almost intolerable. The gradient direction map shows that the ceiling closest to the window reflects a great deal of light into the classroom, but the classroom itself does not seem to be evenly illuminated. A designer's solution to this classroom might be to add reflectors closer to the windows so that the daylight coming in can reflect evenly throughout the space. The designer can also use an indirect/direct electrical fixture instead to reflect off of the ceiling and be diffused into the classroom.

The third case study considered a space with both electric lighting and daylighting in the lobby of the Business Engineering Science and Technology building at the University of Kansas campus. The lobby has two walls of curtain glass and several LED down lights recessed into the ceiling. Looking at the luminance map, one can see that there is an even illumination in the lobby space. Most of the light that might cause glare is coming from the curtain wall of glass and from the light reflected onto the ceiling



although, according to the data points, the glare at this time of day from the window is almost imperceptible. The down lights have the most illuminance but they do not seem to cause glare in the space. The space does not necessarily need to be improved but a designer may add a clear film on the curtain wall glass to diffuse the light.

The last case study looked at an exterior lit space, specifically a high school in Overland Park, KS. There is not much potential for glare since this photo was taken at night. In fact, in this situation, it is better to have more light so that the students at the school can feel safe and so they can see the exterior parking lot more clearly as they exit the building. One can see from the gradient magnitude map that the main lights are most clear and that the façade of the high school is well lit. However, the logo of the school is not shown. A designer might be able to improve this space by adding better lighting to the façade and emphasizing the light on the school logo for aesthetic appeal.

Moreover, for this paper, a questionnaire was sent out to entry-level and advanced designers in the field. Several questions were asked about luminance maps, gradient maps, gradient direction maps, and more. Outcomes of the questionnaire show that the designers in the field thought that the luminance map and luminance gradient map was easy to understand and that designers would be interested in using it in aiding their design practice. From the questionnaire and the case studies, this method proves to be very useful for students and entry-level designers in that they can successfully evaluate an environment in a couple of hours to assist in their lighting design practice, which otherwise would take years of experience accumulated in a work environment.

As a result, the consumer-grade camera aided HDR imaging method has been proven to be useful for entry-level designers in the field of lighting design. The method

can facilitate the understanding and evaluation of lighting design. The HDR images produced, the luminance maps, and the gradient maps that are field measured are in-line with the human visual perception. The images with plotted luminance and luminance gradient maps are useful for further data treatment such as calculation of luminance contrast and luminance gradient, identification of the precise locations and sizes of glare sources, and to obtain the calculated glare indexes. Given the 18 millions of luminance data embedded on each HDR image, the camera-aided imaging method is also a very useful tool for advanced lighting designers to record the quality of interested luminous environments.

## **5.2 Discussion**

The use of high dynamic range photography has the potential to help lighting designers in the field. The lighting designer can benefit from this tool in many ways such as understanding the potential hazardous glare sources and understanding the luminance gradient. Although this tool has a lot of potential to be highly beneficial in the lighting design industry, it still has some limitations which are listed as follows:

- Most designers in the field of lighting design are visual and creative. HDR photography is simply too time consuming and too difficult to understand for the basic designer. A designer might not want to go through all of these steps to analyze an existing space.
- In the questionnaire that the designers answered, it has indicated that the luminance map and luminance gradient magnitude map was simple to understand, however the luminance gradient direction map and the 3D luminance gradient

map are difficult to understand. The designers in the field would need a simpler way to understand and analyze the photos.

- Most designers do not know how to use MatLab code and are not interested in learning the language. The HDR photography tool is not currently placed in any simple computer programs such as AGI or Revit.
- Most designers do not have time to photograph an existing space at different hours of the day. Timing is often not a concern for electrically lit spaces; however, in daylit spaces it is a concern due to the ever-changing daylighting conditions in a space.
- Although HDR images provide a lot of useful data, the data might be too difficult for a designer to understand. It does not provide additional information such as geometry of a room and information about human factors that designers may need.

With all of these limitations, there are still many aspects to HDR photography that are highly beneficial for a designer. Some of those benefits are as follows:

- The HDR images and luminance maps show what the human eye cannot see. The images help the designer achieve a better understanding of an existing space and how it might potentially be improved.
- The designers can look at a luminance map and understand where there may be potential for glare. This may especially be beneficial in classroom or office spaces where a designer would like to prevent glare.

- The gradient direction map is beneficial for a designer to understand which direction the light is going. This would assist a designer in deciding which direction they would like to aim a light, if a specific spot in a space needs to be emphasized.
- When a designer looks at the HDR images and the luminance maps, they can get a better understanding of the existing space and how it can be improved. After analyzing an existing space, a designer might be able to improve their design for another space in the future or renovate the existing space to their intended desires.
- The tool is useful for designers to evaluate the quality of luminous environments resulted from non-uniform daylight and electric lighting in existing spaces.

In addition, the use of HDR photography can be very beneficial for designers in the lighting design industry. The main challenge is the ease of use for designers. More designers would use this tool if it was easier to use or if it was placed on a computer program such as AGI. Instead of only being able to analyze in existing space in real life, a designer potentially can draw the space on a computer program, place the sketch into the program and analyze it through the same computer program. If it were simpler to use, many designers would undoubtedly be more interested in using it.

Also, if the tool itself were more visually appealing, it would be more beneficial for designers in the field. Designers do not have time or interest in learning how to take an HDR image or how to use MatLab code to analyze the images. If there was a simple application available on the computer, the designer could simply take a photo at a specific time of the day and place the photo into the computer program. The computer

program would then give output data of the HDR images and provide all of the information needed.

A designer also would be more likely to use this tool if the camera-aided imaging method gave simple information to help interpret how the users in the space might feel with particular lighting conditions. For example, if the output data were less than 10 foot-candles in an office space, a program would say that the illuminance in the space is not comfortable for the users. However, if the space was a movie theatre, for example, the program would say that the users would feel comfortable in the space. This would be a more practical use of this tool in the future. Another idea to make this tool easier to use is to make a phone application where the user can simply download the application to their smart phones, e.g., an iPhone with sequential exposures to make HDR images, and snap a photo of an existing space.

To conclude, the use of high dynamic range photography is a very beneficial tool that shows the potentials for lighting quality evaluation such as glare assessment in a space and that provides specific glare indices values such as DGP, DGI, UGR, and VCP. Although the tool in its current format may not be simple enough to use on a day-to-day basis in the field of light design, future developments can make HDR photography an easy-to-use, beneficial tool from which designers across the field with various levels of expertise would benefit.

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